AN INVESTIGATION OF

THE RESISTANCE OF STRUCTURES

TO

INTEGRATED NUCLEAR WEAPONS EFFECTS

A MASTERS THESIS

by

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INTRODUCTION

Object and Scope

It is generally considered at the present time that the basis of the balance of power in the world is the capability of waging thermonuclear war. This was demonstrated all too pointedly in the Cuban missile crisis in 1962.

The specter of nuclear war should never become a reality if the national policy of deterrence through threat of full retaliation functions as planned. This policy depends on a rational enemy response to the fact that American retaliation to enemy attack would in turn inflict unacceptable damage on the attacker. But what if an enemy does not act rationally? What if an attack is launched accidentally, or through a misunderstanding or miscalculation? It is this possibility against which the nation must be protected. The questions which subsequently arise are: how is this protection to be effected, and what are its economic and practical limits? The variables to be considered in a possible enemy attack are many. What targets would be attacked? How many weapons would be employed? Of what magnitude would they be? How would they be delivered? Would they be air or surface blasts?

Probability studies undertaken by the Department of Defense

under various combinations of the conditions mentioned above have resulted in data which is helpful in answering questions concerning the type and degree of protection which should be provided.[1] These data indicate that in the event of an all-out nuclear attack, with no shelter provided, many millions of people would survive the immediate blast and heat effects of the weapons, only to be further threatened by lethal or disabling fallout radiation which would follow. It is this group of people that the nation's civil defense program is designed to protect.[2] This protection is basically in the form of a nationwide fallout shelter system which would shield people from the dangerous gamma radiation associated with fallout until the radiation intensity outside the shelter decreases to a safe level.

In support of this program is this statement by President Johnson:

> While confident that our present strength will continue to deter a thermonuclear war, we must always be alert to the possibilities for limiting destruction which might be inflicted upon our people, cities and industry should such a war be forced upon us.
>
> Many proposals have been advanced for means of limiting damage and destruction to the United States in the event of a thermonuclear war....any comprehensive program would involve the expenditure of tens of billions of dollars. We must not shrink from any expense that is justified by its effectiveness, but we must not hastily expend vast sums on massive programs that do not meet this test.

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[1]<u>Department of Defense Fallout Shelter Program</u> (Washington: Department of Defense, Office of Civil Defense, June, 1964), p. 1.

[2]<u>Civil Defense</u> - 1965 MP-30 (Washington: Department of Defense, Office of Civil Defense, April, 1965), p. 4.

> It is already clear that without fallout shelter protection for our citizens, all defense weapons lose much of their effectiveness in saving lives. This also appears to be the least expensive way of saving millions of lives, and the one which has clear value even without other systems.[3]

As the first phase of their operations, in 1961 the Office of Civil Defense began a national survey to locate potential public fallout shelter space in existing structures. As of the first of April, 1965, the survey had located more than 151,000 structures throughout the United States which contain potential public fallout shelter space for more than 131,000,000 people.[4] The total needs of the nation are in excess of two hundred million spaces. This difference must be met largely through the creation of shelter in new construction and by the improvement of existing structures possessing good shelter potential. This can be done with relatively minor changes in construction, called "slanting," which includes such measures as thickening walls, blocking off ground area windows, providing additional ventilation to certain spaces, raising window sills, and other similar modifications.

In order to further the shelter program, and to demonstrate that low-cost fallout shielding can be incorporated into structural design in varied and imaginative ways without sacrificing functional or aesthetic requirements, the National School Fallout Shelter Design Competition was held. Twenty-six winning designs from this competition were incorporated

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[3]From the President's special message to Congress on national defense, January 18, 1965, quoted in Civil Defense-1965, op. cit., p. 4.

[4]Civil Defense-1965, op. cit., p. 11.

into a booklet published by the Office of Civil Defense. These designs presented a wide variety of solutions to the shielding problem, some of them being almost completely underground, others nearly all above ground, and others employing a combination of surface and subsurface construction.

A recently initiated project of the Office of Civil Defense is an investigation of the bonus capacity of shielded structures to resist the effects of nuclear weapons other than those associated with fallout, i.e., the blast and thermal effects. The object of this study is to determine how to maximize the total resistance of a structure to integrated weapons effects, with few and relatively minor modifications in design, without actually creating a hardened structure.

The basis of this investigation is an evaluation of the winning designs of the National School Fallout Shelter Design Competition. This evaluation consists of a determination of the capacity of each structure to resist integrated nuclear weapons effects, and the summarization of the individual evaluations into an overall criteria for any conventional above-ground structure. Included in each evaluation are the following considerations:

(1) The inherent bonus protection of the structure against integrated nuclear weapons effects.

(2) The advantages and disadvantages of the design from the integrated effects standpoint.

(3) Recommended design modifications to increase the total

protection of the structure through minor changes.

It is the object of this report to present the problems involved, the methods of analysis employed, and the results of the investigation outlined above.

Notation

A_c = cross sectional area of concrete

A_s = area of tension reinforcing steel

a = width of beam

b = width of contributory load area

c = pressure factor

d = effective depth of tension steel reinforcement

d_b = width of exposing structure perpendicular to exposed wall

d_o = distance from exposed structure to exposing structure

d_1 = width of combustible storage yard perpendicular to exposed wall

d_2 = distance from exposed structure to combustible storage yard

E_e = exposure severity index

F = shape factor loading force

F_r = roof shape factor

F_w = adjacent wall shape factor

F_y = storage yard shape factor

f'_c = concrete strength

f'_{dc} = dynamic concrete strength

f_y = steel yield strength

f_{dy} = dynamic steel yield strength

f_p = extreme flexural fiber stress due to overpressure

H = height of structural element

H_b = height of exposure building

HF = heat factor

h_a = location from which shape factor is measured

k = horizontal stress constant

L = span length in structural computations parameter used in determining storage yard shape factor in thermal computations

L' = parameter used in determining roof shape factor

M_{max} = maximum moment

N = parameter used in determining storage yard shape factor

N' = parameter used in determining roof shape factor

P = axial load

P_u = ultimate axial load capacity

P_m = peak loading overpressure (concentrated)

p_m = peak loading overpressure (uniform)

p_{so} = peak side-on overpressure

Q = resistance to concentrated loading

q = fire load index: structural resistance to uniform loading

q_e = exterior fire load index

q_{eb} = exposure building fire load index

q_{ey}	= combustible storage yard fire load index
q_f	= flexural resistance
q_v	= shear resistance
q_y	= diagonal tension resistance
RWF	= roof and wall factor
SF	= storage factor
T	= fundamental period of vibration
t	= duration of side-on overpressure: least width of column
t_c	= clearing time
t_i	= impulse duration for overpressure
V_{ult}	= total shear acting at a distance d/2 or 0.1 L away from the support, whichever is smaller
W_b	= half-width of exposing structure parallel to exposed wall
W_y	= half-width of combustible storage yard parallel to exposed wall
w	= uniform load
w_{eb}	= weight of combustible material in exposure building
w_{ey}	= weight of combustible material in storage yard
X_1	= parameter used in determining adjacent wall shape factor
Y_1	= parameter used in determining adjacent wall shape factor
Y_2	= parameter used in determining adjacent wall shape factor
Z	= section modulus

α_z = depth attenuation factor

γ = ratio of compression tension steel at midspan of beam

μ = ductility ratio

ϕ_c = percentage of tensile steel at midspan

ϕ_e = percentage of tensile steel at supports

ϕ_t = total percentage of reinforcement

ϕ_v = percentage of web steel

WEAPONS EFFECTS

General Effects

When any explosion takes place, whether it is a stick of dynamite or a thermonuclear weapon, the basic phenomenon which occurs is a sudden release of energy. Some of this energy creates the characteristic flash of light, more is projected outward in the form of heat rays, while the largest portion is used in converting the products of the explosion into gaseous form. This ball of hot gasses expands at a rate which causes a shock wave of compressed air to accompany it as it moves outward from the explosion point. As the shock wave passes an object, two effects are produced, in rapid succession. The first is an overall crushing effect, as the compressed air of the shock wave passes, and the second is a drag effect as the wave attempts to pull the object after it.

In a nuclear explosion, the same phenomena just described take place, on an awesomely large scale. A nuclear explosion also includes an additional parameter in the form of radiation effects. A part of this radiation energy is dispersed instantly at the time of the blast over a limited area, and is called initial radiation. The remainder of the radiation energy is distributed over a period of

time, principally as radiation from fission products which are drawn up into the mushroom cloud, distributed by the wind, and spread over a wide area in the form of fallout.

The magnitude of a nuclear blast is usually measured by comparing its energy release with the amount of TNT that would be required to duplicate it. This comparison is usually expressed in terms of kilotons or megatons (thousands or millions of tons of TNT, respectively). As an example, it would require a stack of TNT the size of five Empire State Buildings combined to equal the effect of one ten-megaton nuclear explosion.[5]

There are two methods used to release the enormous amounts of energy locked in the atomic nucleus. The first of these, termed fission, occurs when the nucleus of a heavy element such as one of the uranium isotopes is broken up into two lighter nuclei, called fission products. The mass of the fission products is less than that of the original atom, and the excess is transformed into energy. If the fission process were perfect (it isn't) one ounce of nuclear fuel would produce the energy of one million pounds of TNT. Weapons based on the fission process are generally known as "atomic" weapons. The second method is called fusion, which occurs when two lighter nuclei are joined together to form one heavier one. This process requires a great amount of heat, so great in fact that it is available only in the energy released in a

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[5]As an aid to continuity, a ten megaton surface burst is used as a standard throughout this study.

fission reaction, which is used as a triggering device. The fusion reaction, in turn, causes further fission to take place and the chain reaction results in the vast release of energy which is characteristic of a fusion, or thermonuclear, weapon.

Sequence of events.

Millionths of a second after a nuclear explosion takes place, the extreme heat created, which is in the range of tens of millions of degrees, causes a brilliant flash of light many times brighter than the sun, and radiates great amounts of energy. An intensely hot fireball is formed of air and weapon residues. In a ten-megaton burst, the maximum diameter of the fireball will be in excess of three miles. In a surface burst, the heat of the fireball vaporizes thousands of tons of earth, which are drawn up into the fireball as it expands and rises. Strong afterwinds on the earth's surface also cause a great deal of dirt, dust and other debris to be sucked into the fireball.

Thermal radiation, which comprises 35% of the weapon's total energy (Figure 1), is emitted from the fireball in two pulses. The first of these lasts only a fraction of a second and is a comparatively minor hazard. The second pulse lasts for a number of seconds and carries about 99% of the total thermal radiation energy. The first pulse, due to the very high surface temperature of the fireball, is in the easily attenuated ultraviolet region while the second is emitted from a slightly cooler surface, and consists mainly of visible and infrared light. This radiation can cause skin burns and ignite fires

many miles from the ignition point of the weapon.

Following the thermal flash the blast wave begins to move out from the fireball. The shock wave from the explosion travels outward at a rate greater than the velocity of sound, creating what could be termed a "moving wall" of highly compressed air. When the blast wave, traveling outward as a constantly expanding sphere, strikes the earth's surface, it is reflected, and the reflected wave which is produced is also capable of producing damage. At some distance from the point of the explosion, the original and reflected blast waves fuse together, creating a shock front with about twice the overpressure (pressure in excess of atmospheric) of the original blast wave. This phenomena is known as the "Mach effect," and the newly created wave front is called the "Mach stem" or Mach front" (Figure 2). In a contact surface blast, the incident and reflected waves coincide, and all objects and structures on the surface, from the explosion point outward are subjected to air blast similar to that of the Mach front of an air burst. As the Mach front advances, the overpressure produced decreases steadily due to lost energy and the increasing area of the advancing front. The overpressure acts in all directions, like a fluid, producing a crushing effect on above-ground structures.

In addition to the overpressure caused by the shock wave, there occurs a "dynamic pressure" which is caused by the high-velocity transient winds which accompany the passage of the blast wave. The peak dynamic pressure actually exceeds the peak overpressure

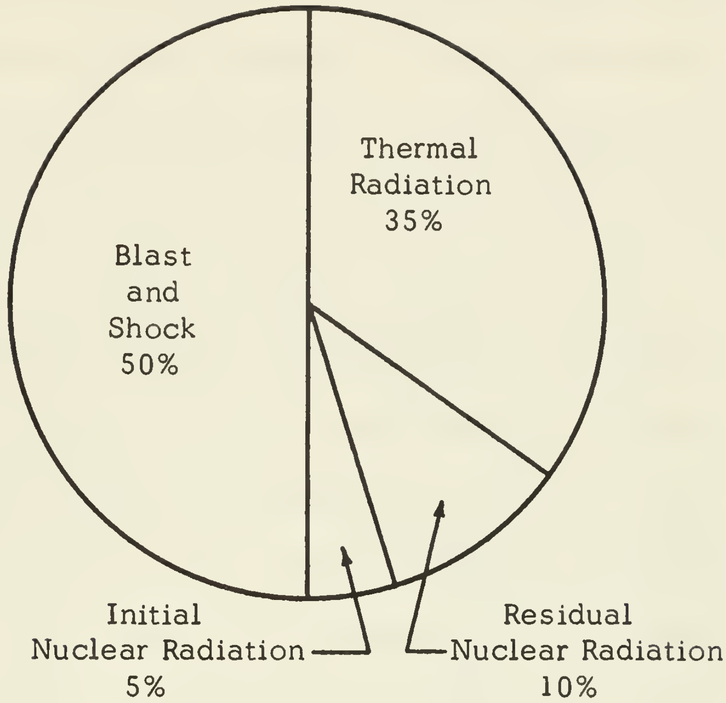


Figure 1. Distribution of energy in a typical burst of a low altitude fission weapon.

--<u>The Effects of Nuclear Weapons</u>, p. 8.

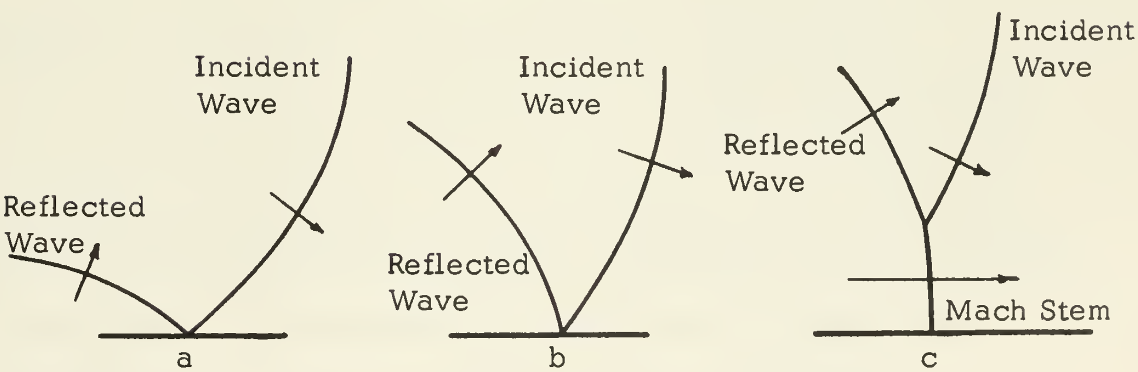


Figure 2. Fusion of incident and reflected waves and formation of Mach stem.

--<u>The Effects of Nuclear Weapons</u>, p. 112.

for very strong shock fronts, while for overpressures below 50 pounds per square inch (psi) the dynamic pressure is considerably smaller. The winds causing the dynamic pressure have velocities exceeding 100 miles per hour as far as eight miles from the explosion point of a ten-megaton surface burst, with much higher velocities nearer ground zero.

As the pressure in the blast wave decreases, it actually sinks below atmospheric pressure, causing a negative pressure phase. The negative pressure phase is also accompanied by a transient wind creating a dynamic pressure, which acts in the opposite direction of that of the positive phase. Both the overpressure and the dynamic pressure accompanying the negative phase are smaller than in the positive phase, and the amount of damage caused is correspondingly less. Figure 3 is an illustration of the manner in which the overpressure created at a particular point by a blast wave varies with time.

The nuclear radiation emitted in connection with a nuclear explosion is of two types. The first of these is the initial or "prompt" radiation which is emitted from the fireball and radioactive cloud within the first minute after the explosion. The initial nuclear radiation includes neutrons and gamma rays which are given off almost instantaneously with the explosion as well as by material in the radioactive cloud. Alpha and beta particles are also given off, but are attenuated so quickly that neither is of much importance. The initial nuclear radiation problem is a local one, as it is lethal only over an area of about the size of the fireball itself.

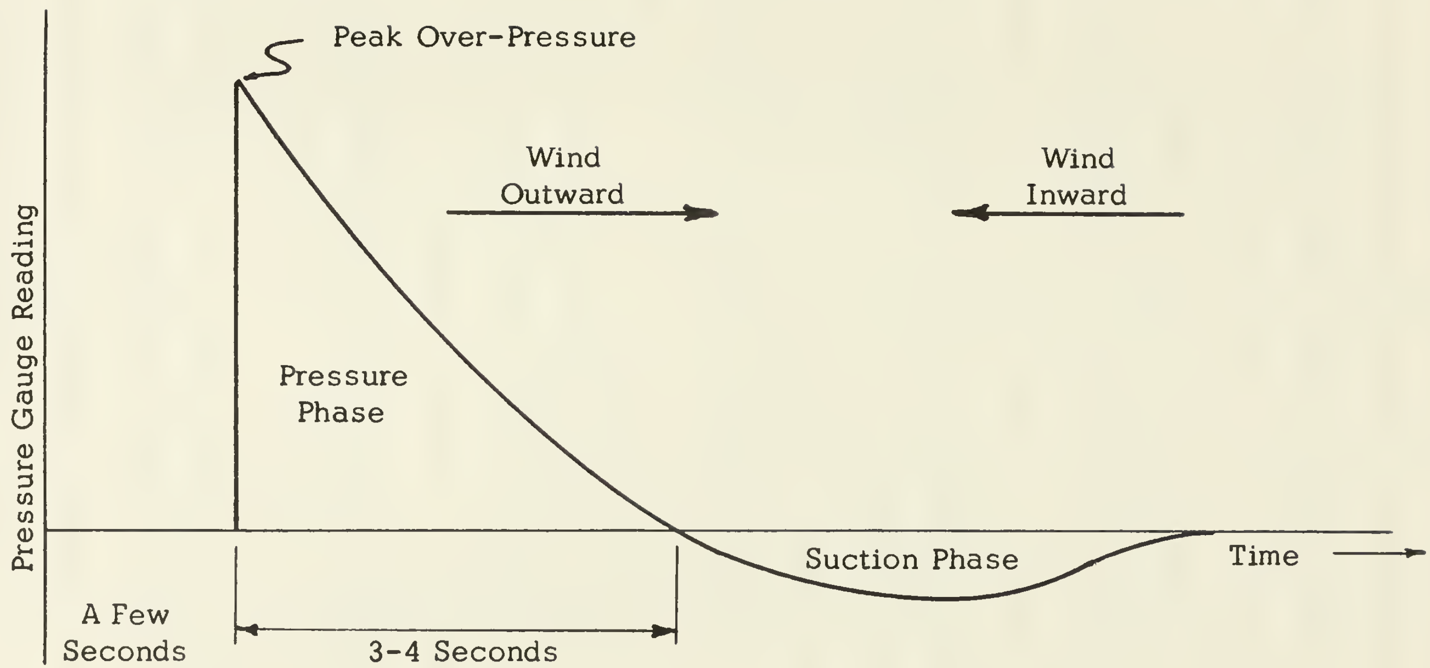


Figure 3. Overpressure created at a particular point by air blast, showing how it changes as time passes after a nuclear explosion.

--Martin and Latham, p. 65.

The second type is residual or fallout radiation, the source of which is radioactive particles formed and carried aloft by the nuclear explosion, which later settle on the earth as radioactive fallout. Fallout radiation includes alpha, beta and gamma rays, of which the gamma rays pose the principal problem. It is convenient to separate fallout into two categories, namely early and delayed. Early fallout, sometimes called local fallout, is much quicker to take effect, and is far more dangerous. It is this early fallout, resulting from surface or low air bursts, which within hours can contaminate large areas with radiation of a sufficient intensity to be an immediate biological hazard. Fission products from the explosion adhere to larger particles of debris, and settle to the earth in a matter of hours. The heavier particles settle in the first hour or two, while lighter ones take more time, and can be spread over hundreds of square miles, depending on the prevailing winds and height of the radioactive cloud (Figure 4). Early fallout is that which reaches the ground in the first 24 hours following a nuclear explosion. Delayed fallout consists of very fine particles which are carried into the stratosphere and are distributed in low concentrations for a long period of time over a wide range of the earth's surface. The radioactive intensity of these particles gradually diminishes during the extended distribution period. As a result, the net radiation deposited on the earth by the delayed fallout is of comparatively low intensity. This type of residual radiation is sometimes referred to as global, or worldwide fallout.

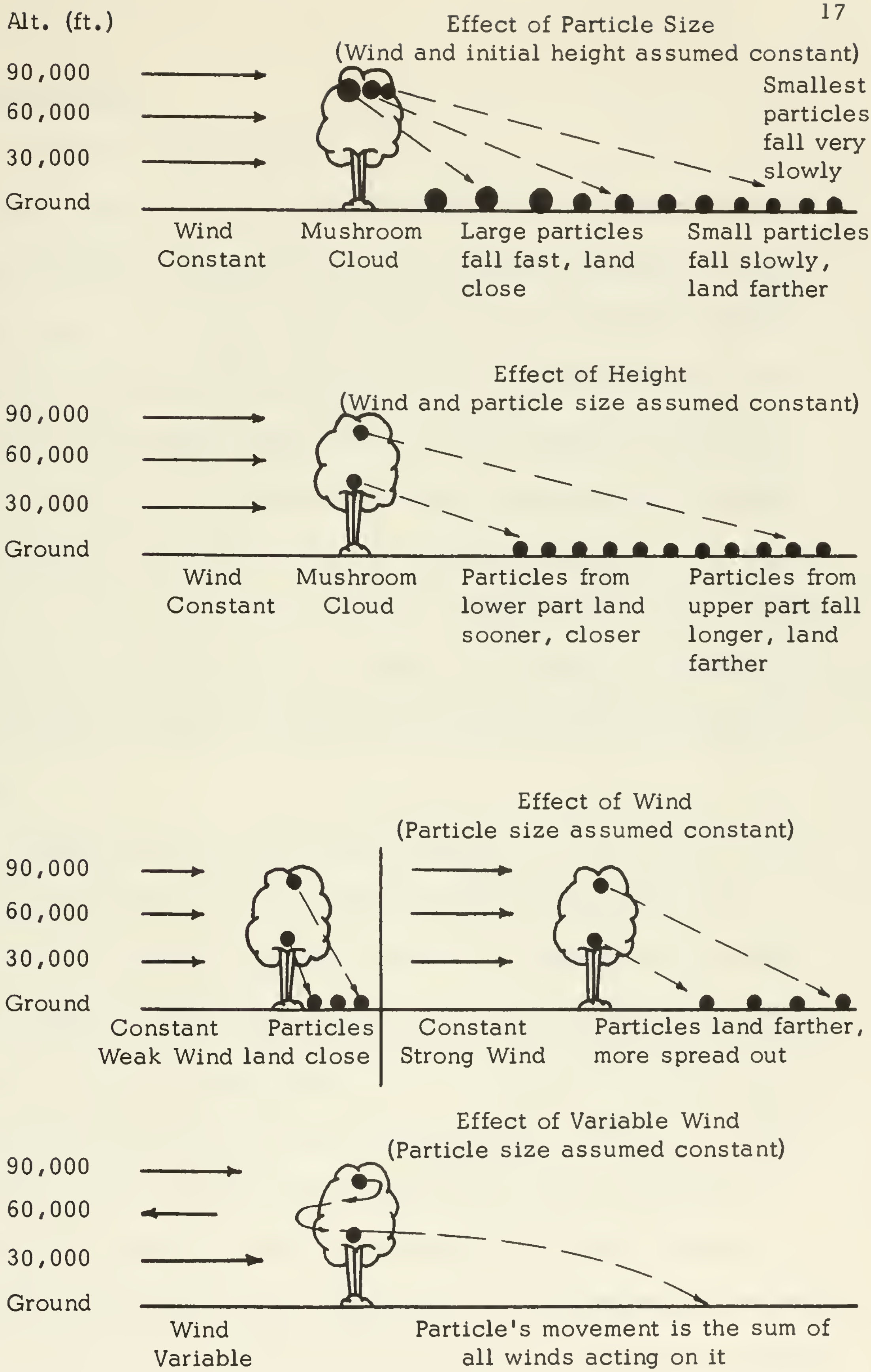


Figure 4. Factors affecting distribution of radioactive particles.

--Fallout and the Winds.

Radiation Effects

A. Fallout characteristics

The initial, or prompt, radiation which occurs during the first minute following a nuclear blast is of an extremely intense and penetrating nature. It is highly lethal and presents specialized shielding problems. However, it is dangerous only in the immediate area of the explosion, where blast overpressures are also extremely high, and while it would have a considerable effect in the planning of hardened blast shelters, it is not a serious consideration outside the immediate area of a surface blast. What must be considered is the deadly residual radiation, or radioactive fallout, which, in the case of a surface burst, contaminates hundreds of square miles downwind from the point of the blast.

Although both early and delayed fallout must be considered in protective planning, the most immediate and serious threat to the population is present in the early fallout. The radioactive particles which descend to earth from the mushroom cloud of a nuclear explosion include over two hundred different forms of radioactive isotopes, each decaying at its own rate by giving off radioactive particles and gamma radiation. Once the fallout has stopped descending, the radiation intensity, or dose rate, which is very high at the start, declines rapidly as radioactive decay progresses. An approximation of the decay rate is that for each increase in time by a factor of seven, the radiation intensity decreases by a factor of ten: seven hours after the dose rate

reaches a maximum at a point, it will be reduced to 10 per cent of its maximum level. Because of this rapid decay rate, the period following a nuclear explosion during which the population must be sheltered against the effects of fallout radiation is not of extreme duration, and in most cases will not exceed two weeks.

It is difficult to predict the area over which fallout will be distributed and the intensity of radiation within this area, even for a specified blast location. Fallout distribution depends on such variables as the speed and direction of the wind at different altitudes, the altitude and type of burst, the amount of energy released, the height of the radioactive cloud, the nature of the ground surface and precipitation conditions in the area. Theoretical fallout distribution calculations assume an ideal wind blowing in one direction at a constant velocity. Such conditions will result in a cigar-shaped pattern, with the radiation intensity diminishing in the downwind direction and toward the outside edges of the pattern (Figure 5). In practice, however, the variables mentioned above come into play, and the actual fallout distribution tends to be highly irregular, with radiation intensities varying widely within the contaminated area (Figure 6).

Because of the highly unpredictable fallout intensity distribution, and because of the huge area affected, it must be assumed that everyone could be exposed to potentially dangerous fallout radiation doses in event of a nuclear attack.

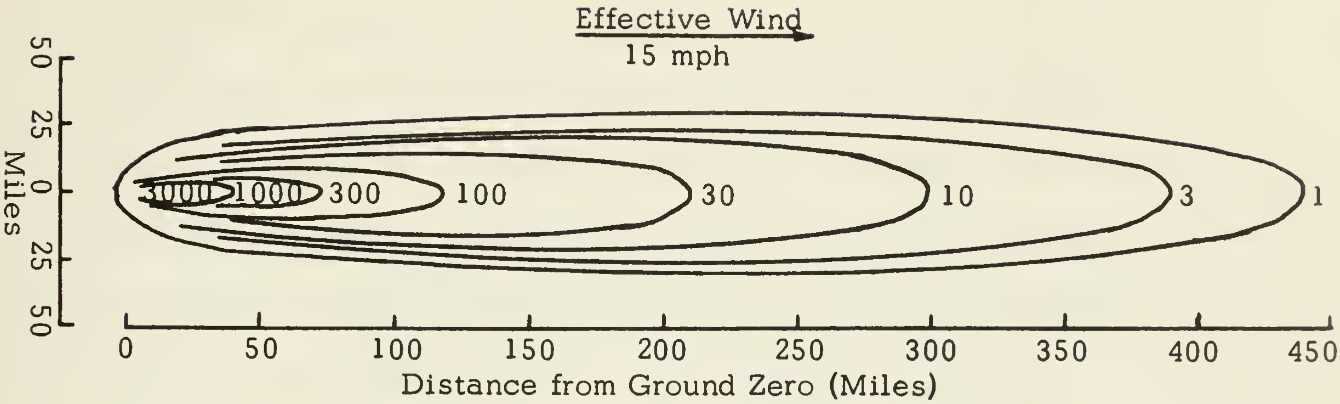


Figure 5. Idealized unit-time reference dose-rate pattern for early fallout from a 1-megaton fission yield surface burst. Dose rate is in roentgens per hour.

--The Effects of Nuclear Weapons, p. 449.

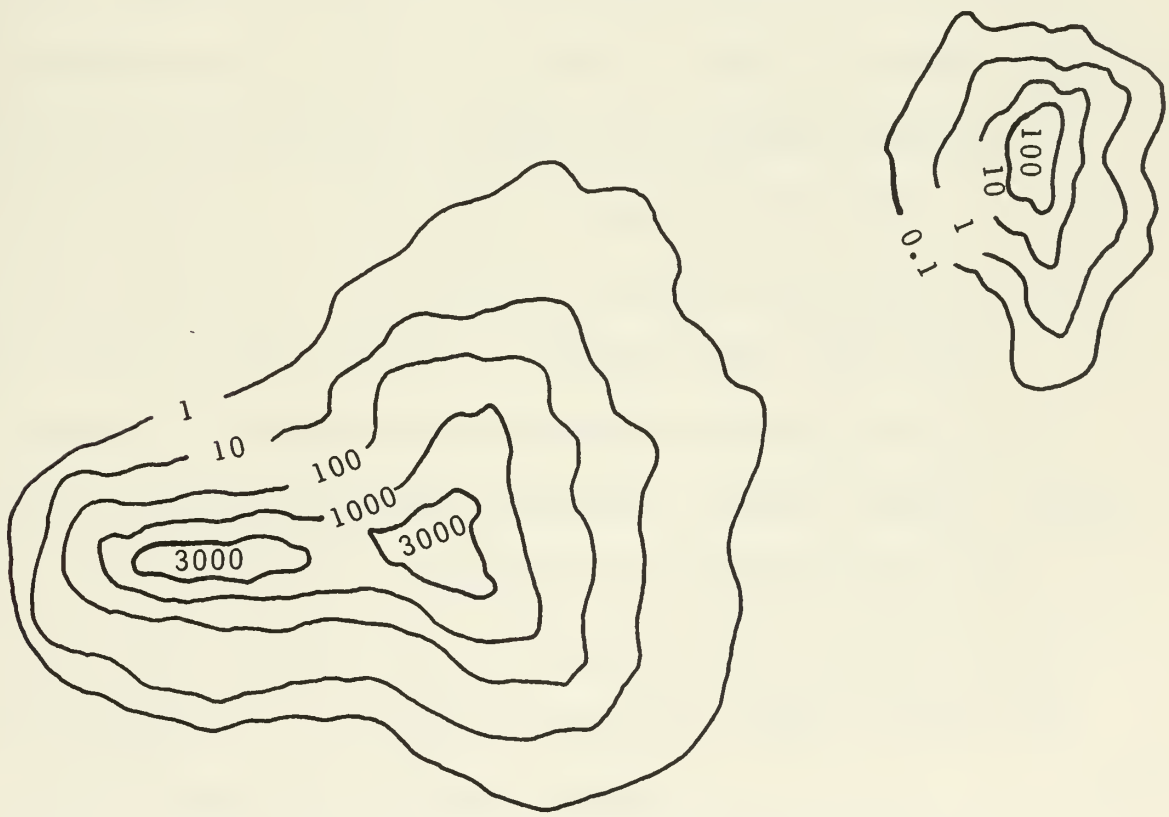


Figure 6. "Actual" dose rate contours illustrating deviations from ideal and the occurrence of downwind "hot spots". Dose rate is in roentgens per hour.

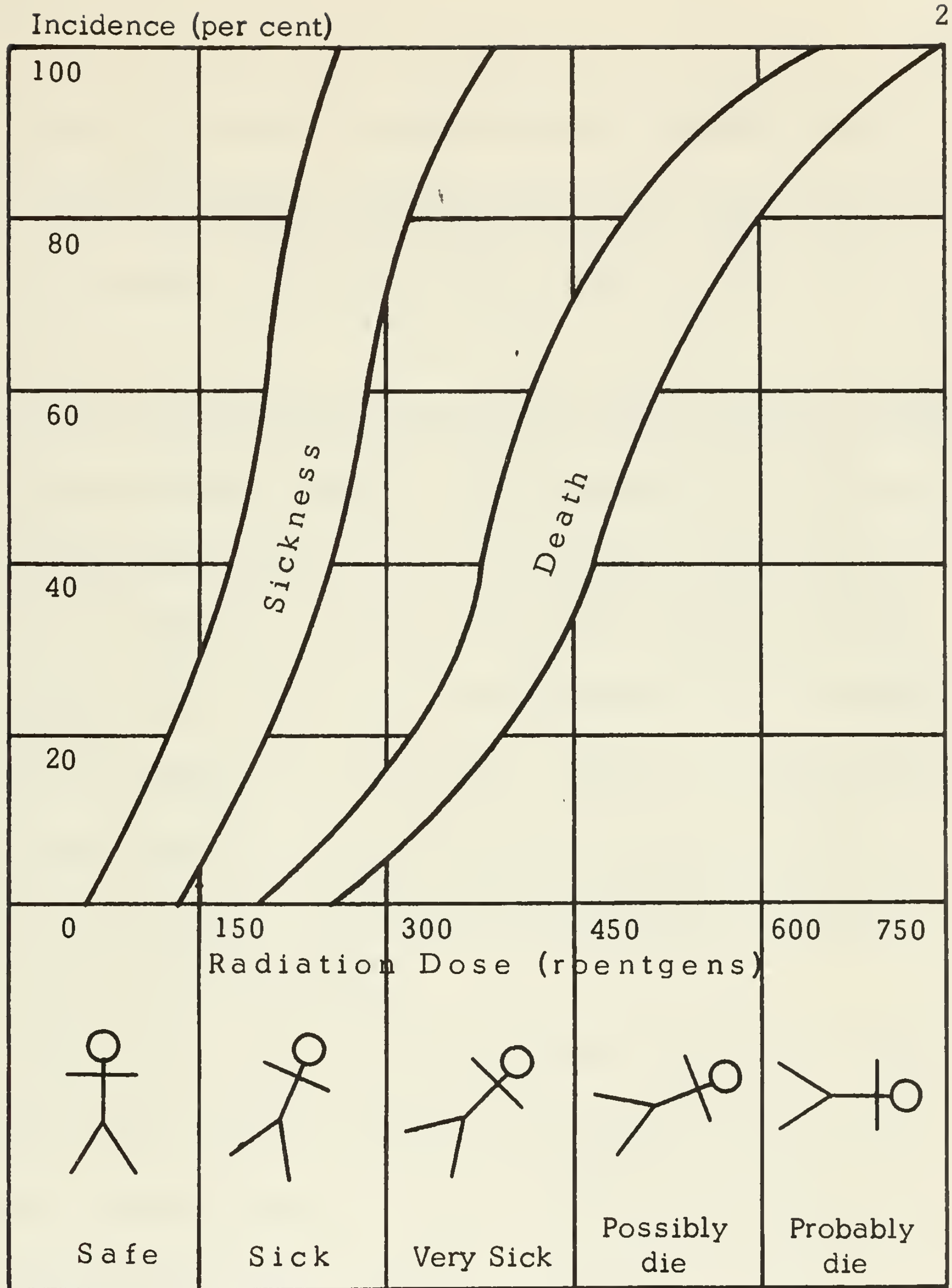
--Martin and Latham, p. 114.

B. Effects on exposed personnel

The effects of nuclear radiation on those exposed to it can vary from death to sickness to no apparent injury at all. The effect depends on the amount of radiation absorbed, the rate at which the absorption takes place, and the physical characteristics of the person affected. The amount of radiation to which a person is exposed is called the "dose." A convenient unit for measuring radiation doses is the roentgen, a measurement of gamma radiation. It is very difficult to establish a relationship between the radiation dose and the accompanying biological effect. Expressing the relationship statistically seems to be the most meaningful approach, as shown in Figure 7. Effects of nuclear radiation which are not immediately detectable in the individual receiving the dose include genetic effects due to mutations in the genes of the human reproductive cells. These mutations may have an abnormal effect on the children of those exposed to a radiation dose. Other effects, sometimes not appearing until years after the radiation dose may include an increased probability of leukemia, cataracts, sterility, cancer, and shortening of life. It is generally believed that the biological damage due to a radiation dose is less severe when the total dose is accumulated over a long period of time such as weeks or months than when it is received in a few hours or days.

C. Fallout shielding

Fallout radiation consists of alpha, beta, and gamma rays. The alpha and beta rays are easily attenuated, and offer no external



Recovery within	1 month	3 months	6 months	---
or Death within	---	6 weeks	4 weeks	2 weeks

Figure 7. Effects of nuclear radiation on personnel. Curves show percentage incidence of sickness and death in a group of exposed persons, for doses accumulated in a few days. Effects prove less severe if accumulated over weeks or months. As indicated at bottom, radiation sickness is usually a drawn-out process.

--<u>Nuclear Attack and Industrial Survival</u>, p. S8.

hazard to sheltered personnel. Any shield which is adequate against the highly penetrating effects of gamma radiation will easily screen out alpha and beta particles, which are usually dangerous only when ingested.

There are two basic methods of protection against gamma radiation. The first, called geometry shielding, involves placing the shelter area such that the effective distance between the radiation source and the persons to be protected is a maximum. Geometry shielding is based on two principles. First, there is a general decrease due to the spread of radiation over larger areas as it travels. The dose is inversely proportional to the square of the distance from the source. Secondly, attenuation is gained due to absorption and scattering of the gamma rays by the intervening atmosphere.

The second method, termed barrier shielding, makes use of the principle that gamma rays are absorbed or attenuated to some extent in the course of their passage through any material. In general, it may be said that the decrease in radiation intensity as it passes through a barrier is dependent upon the mass of the material between the source of the rays and the point of observation. It requires a greater thickness of a substance of low density, such as wood, than one of a high density, such as lead, to attentuate the same amount of radiation. In comparing the attenuation qualities of different materials, it is convenient to make use of a term known as the mass thickness. This is obtained by multiplying the density of a material by its

thickness, the product being the mass thickness of the material in pounds per square foot.

As a means of indicating the degree of protection provided by a shelter, a term known as the protection factor has been established. The protection factor of a shelter is defined as the ratio of the radiation intensity existing outside the shelter to the intensity inside the sheltered area. Empirical methods have been developed to determine the protection factor of any potential shelter, and were employed in the design of the schools of the National School Fallout Shelter Design Competition.

Blast Effects

A. Effects on personnel

There are two types of injuries resulting from the passage of a blast wave. Direct, or primary injuries are those suffered as a result of the variations in pressure which accompany a blast wave, while indirect injuries are those incurred due to flying missiles, or by the violent displacement of the body itself. For a given overpressure, nuclear weapons are considerably more effective than conventional weapons in producing both types of blast-related injuries, due to the comparatively long duration of the nuclear induced pressure phase.

Direct blast injuries, occurring as a result of transmission of pressure waves through the body, include hemorrhage and ruptures of the internal organs, due chiefly to damage at the points where cartilage and bone join soft tissue. The lungs are particularly prone to damage, and such injuries are often the cause of death within minutes after they are received. Some degree of eardrum injury could be

expected, although this injury is probably as much a function of age as it is of the degree of overpressure experienced.

Injuries received from flying missiles vary from simple contusions and lacerations to more serious injuries such as fractures and bodily penetrations, ultimately resulting in death. Injuries of this type, as well as those resulting from bodily displacement depend on such a large number of variable conditions that it is extremely difficult to achieve any relationship between weapon magnitude and range, and the injuries which would occur under these conditions.

Although the estimated overpressure required for a fifty per cent probability of direct blast wave fatality is about 50 psi,[6] some sort of blast related injuries could occur at peak overpressures as small as one or two psi. An approximation of blast effects at various ranges is illustrated in Figure 8.

B. Effects on structures

The basic phenomena associated with a nuclear blast wave have been previously discussed in this report (Pages 12-14). The application of scientific principles basic to these phenomena, with the aid of many tests and laboratory studies, have permitted the derivation of certain relations involving the shock velocity, wind velocity, overpressure, dynamic pressure, and the density of air behind the ideal shock front. These relations have been utilized graphically in describing the per-

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[6] The Effects of Nuclear Weapons, ed. Samuel Glasstone (1st ed. rev.; Washington: Atomic Energy Commission, April, 1962), p. 557.

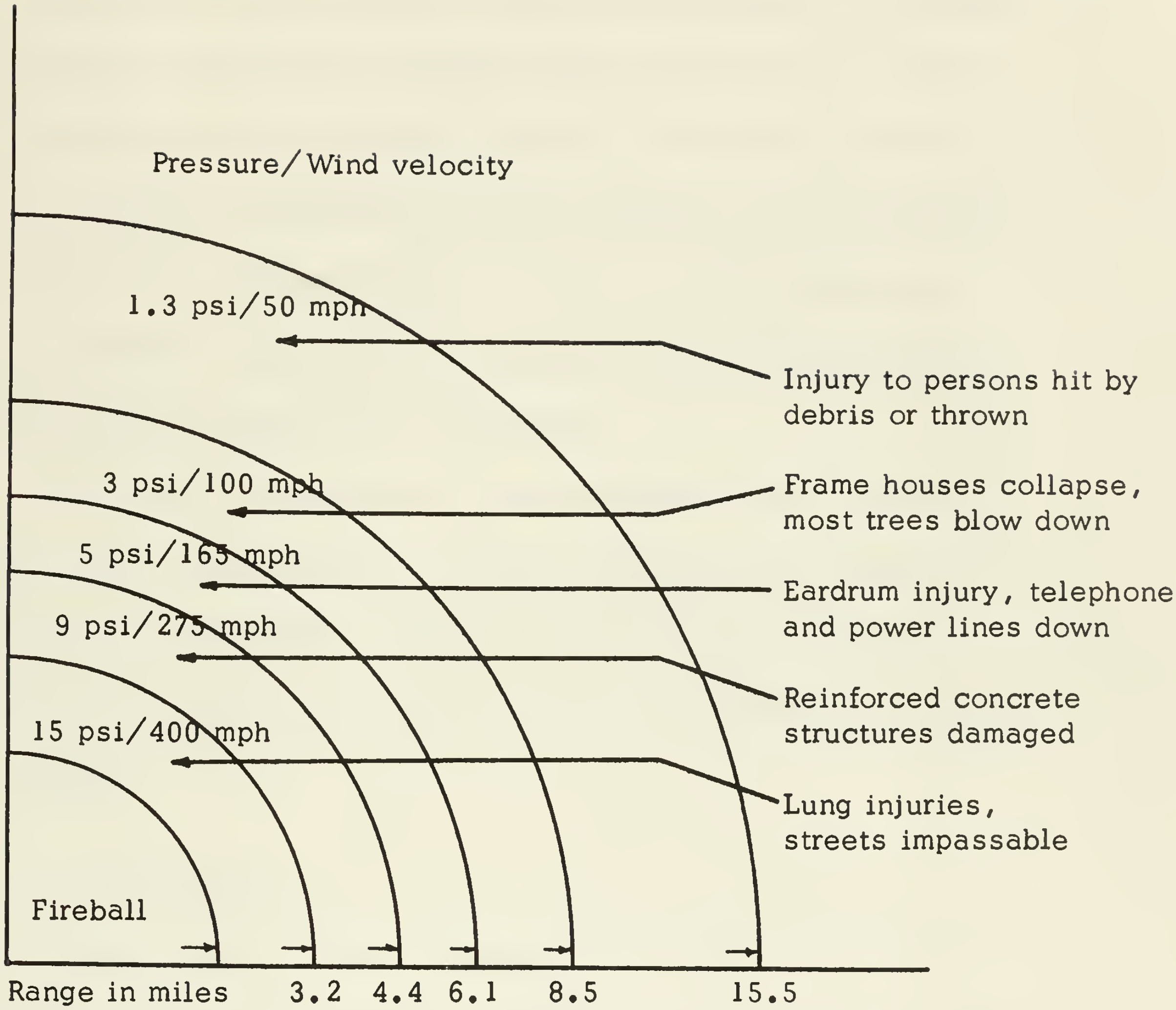

Figure 8. Blast effects of a 10-megaton surface burst. The above figure shows various levels of blast pressure, equivalent wind velocities, and possible effects in the annular zones between successive range circles.

--Nuclear Attack and Industrial Survival, p. S5.

tinent effects of the blast wave at various ranges for various heights and magnitudes of nuclear blasts. Using this information it is possible to consider the interaction of the blast wave with structures and the factors which affect the structural response. As structural response and blast loading are extremely complex phenomena, exact predictions are virtually impossible to achieve. However, by the application of sound judgment to the information available, it is generally believed that results of some value can be obtained.

There are two main aspects to be considered in the interaction of blast waves with structures. The first of these is the "loading" which deals with the forces applied to a structure by a blast wave, and the second is the "response" or reaction of a structure to a particular loading.

C. Loading factors

In dealing with the loading function, it is usual to consider it in two parts: first, the "diffraction loading" which is governed chiefly by the peak overpressure accompanying the blast wave; and second, the "drag loading" in which the dynamic pressure governs.

Diffraction loading begins when the shock front strikes the face of a structure. Reflection of the shock front occurs, resulting in a rapid build-up of overpressure at the building face from two to four times that of the incident wave front. The magnitude of the reflected pressure is affected by such factors as the angle at which it strikes the building face and the peak overpressure of the incident

blast wave. As the blast front moves forward, the pressure wave bends or "diffracts" around the structure, so that the structure is ultimately engulfed by the overpressure, with approximately the same magnitude being exerted on the side walls and roof. The front wall has meanwhile been subjected to the added effect of the wind or dynamic pressure, while the back wall is shielded from it. This pressure differential between the front and back faces produces a force tending to cause the structure to deflect in the direction of the blast wave. This force is at a maximum when the blast wave has not quite completed its diffraction around the structure, with the back face not yet under the influence of the incident overpressure. Once the blast wave has completely surrounded the building, the diffraction loading is reduced, and on closed buildings an inward crushing force becomes prominent, due to the overpressure which then completely surrounds the building. An illustration of the various stages in the diffraction of a blast wave by a closed structure can be seen in Figure 9.

If a structure exposed to a blast wave has a significant number of openings, or easily breached areas such as windows or light doors, a rapid equalization of pressure between the inside and outside of the building would occur, greatly limiting the diffraction loading and the accompanying crushing effect. This type of structure is most vulnerable to the drag loading produced by the dynamic pressure.

The overpressure from the blast wave also travels through the ground, affecting underground structures as well as the foundations of

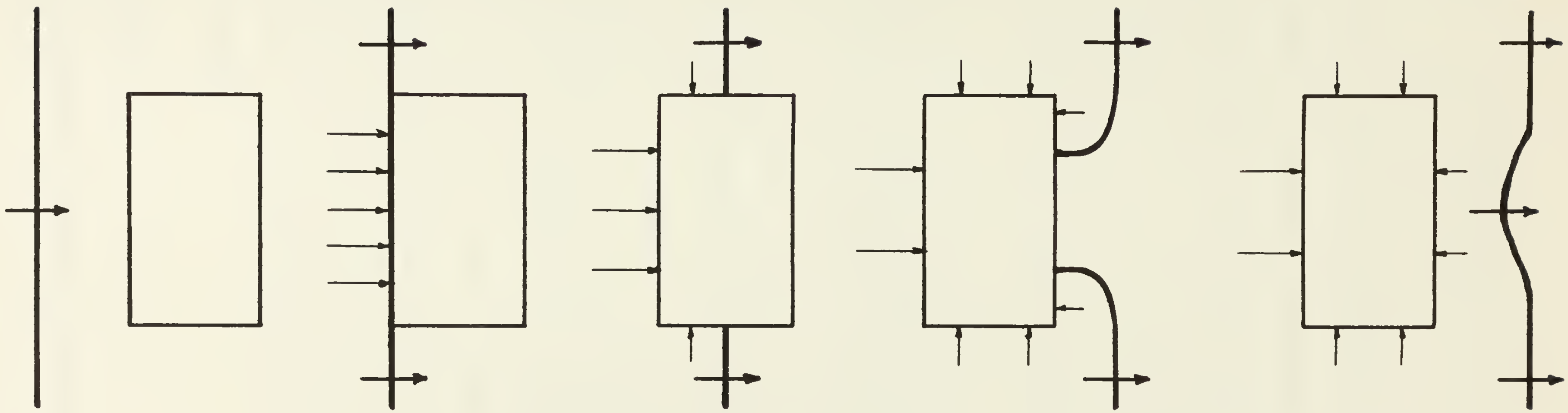

Figure 9. Stages in the diffraction of a blast wave by a structure without openings (plan view).

--*The Effects of Nuclear Weapons*, p. 152.

aboveground structures. For shallow underground structures the roof loading is considered to be the same as that on the ground surface above. On vertical walls of underground structures, where the water table is considerably below the surface, the horizontal blast-induced pressure is a function of the peak overpressure on the ground surface; while for a water table very near the surface, the horizontal blast-induced pressure is considered equal to ground surface peak overpressure.

Throughout the duration of the positive overpressure phase, a structure is subjected to drag loading as a result of the dynamic pressure created by the transient winds which accompany the blast front. The drag loading is like the diffraction loading in that it acts as a lateral or translational force on the affected structure. For overpressure values less than 50 psi, the dynamic pressures are considerably less than the peak overpressures which they accompany. On the other hand, the drag loading is of considerably longer duration than the diffraction loading, lasting for a number of seconds; while the diffraction loading is effective for only a fraction of a second. The drag loading on a structure depends not only on the dynamic pressure, but on the shape of the structure. The shape factor is expressed by the drag coefficient which is less for rounded or streamlined objects than for those which are irregular or sharp edged.

D. Response factors

There are many factors which influence the response of a

structure to a blast wave. Among the most important of these are the structure's strength and mass, its general structural design, and its ductility.

The most basic of these criteria governing structural response is the strength of the structure. The "strength" of a structure in this regard is affected by a number of factors. These include the massiveness of construction, ductility of the frame, strength of connections, redundancy of supports, and the amount and type of diagonal bracing which is incorporated.

Most structures in the United States are designed to resist only the lateral load produced by high winds. For design purposes, these wind loads are considered to be static. The lateral loading produced by a nuclear blast wave, however, is of a dynamic nature. The load is applied rapidly and lasts for a second or more with continuously decreasing strength. Thus the inertia of a structure, as measured by the mass, is an important factor in determining response to a dynamic lateral load, although it is not significant for static loading. Structures which have been designed to withstand earthquake loading, often of continuous design and stiffened by diaphragm walls to provide rigidity, have the best chances of resisting the lateral forces applied by a nuclear blast wave.

Ductility is a measure of the degree to which a material or structure is able to absorb energy without failure. A structure which is to undergo as little damage as possible from a nuclear blast

should have as much ductility as possible. Structural steel and reinforced concrete buildings both have a high degree of ductility, and a corresponding ability to absorb the energy load resulting from the passage of a blast wave.

Methods of design and analysis have been developed to cope with the problems of blast loading. Procedures contained in D.M. Newmark et al Air Force Design Manual AFSWC-TDR-62-13B (Kirtland A.F.B., N.M.: U.S. Air Force, Dec. 1962) were used as a basis for the blast analyses included in this report.

Thermal Effects

A. General characteristics

Due to the extremely high temperatures in the fireball created by the explosion of a nuclear weapon, a great amount of energy is released in the form of thermal radiation. The effective thermal radiation is defined as that which is emitted from the fireball within the first minute following detonation.[7] In surface and air bursts, the thermal radiation is emitted in two pulses. The first of these is predominantly in the easily attenuated ultra-violet region and lasts less than a second, while the second pulse consists mainly of visible and infrared radiations, and continues for a number of seconds, the time varying with the energy yield of the explosion. It is about thirty seconds for a 10 megaton burst.

The characteristics of the thermal flash have been compared to

[7]Ibid., p. 317.

those of a red-hot burner on a stove.[8] The heat from such a burner can be felt at a considerable distance, the intensity increasing rapidly as the distance to the burner is reduced. At close ranges it is possible to ignite easily combustible material without actually touching the burner. Skin burns can be received in the same manner. The thermal radiation resulting from a nuclear explosion produces these same effects of skin burns and the spontaneous ignition of combustible materials, but at very great ranges, due to the extreme heat created in the fireball.

Unless it is scattered by the atmosphere, thermal radiation travels in straight lines from the fireball, as would ordinary light. Protection from thermal radiation is provided by any solid, opaque material between the fireball and the object to be shielded. Transparent materials such as glass or plastic, however, transmit thermal radiation with but a small degree of attenuation.

Under certain atmospheric conditions, thermal radiation undergoes considerable scattering, and will arrive from all directions, rather than in a straight line from the burst point. This effect must be considered in planning thermal radiation shielding.

B. Effects on personnel

The principal effect of thermal radiation on personnel is skin burns, with effects varying from minor distress to death. Direct

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[8]Thomas L. Martin, Jr. and Donald C. Latham, <u>Strategy for Survival</u> (Tucson, Ariz.: The University of Arizona Press, 1963), p. 79.

or "flash" burns are a result of the absorption of radiant energy by the skin of an exposed individual, while indirect burns are a result of fires started by the thermal radiation. The indirect burns are the same as those caused by any fire regardless of origin.

Burns are generally classified according to the degree of the injury. First degree burns indicate a reddening of the skin, as in sunburn. Second degree burns are more severe and are characterized by blistering. In third degree burns the full thickness of the skin is destroyed. The distances at which varying degrees of flash burns and other thermal effects are produced by thermal radiation from a ten megaton surface burst can be seen in Figure 10.

Another possible effect of the thermal flash is eye damage. Should a nuclear explosion take place within a person's field of vision, the focusing action of the lens of the eye would concentrate sufficient thermal radiation to burn the retina of the eye irreparably. Since the chances that an individual will be looking in the direction of a nuclear blast at the time of detonation are small, this should not be a widespread injury. What would be more frequent would be a temporary loss of vision, termed flash blindness, which, due to the extreme overall brightness created by a nuclear blast, would be experienced no matter which direction an individual is facing. From a few seconds to several days may be required for the eye to return to normal.

C. Effects on materials

When thermal radiation impinges on any material, part of it is

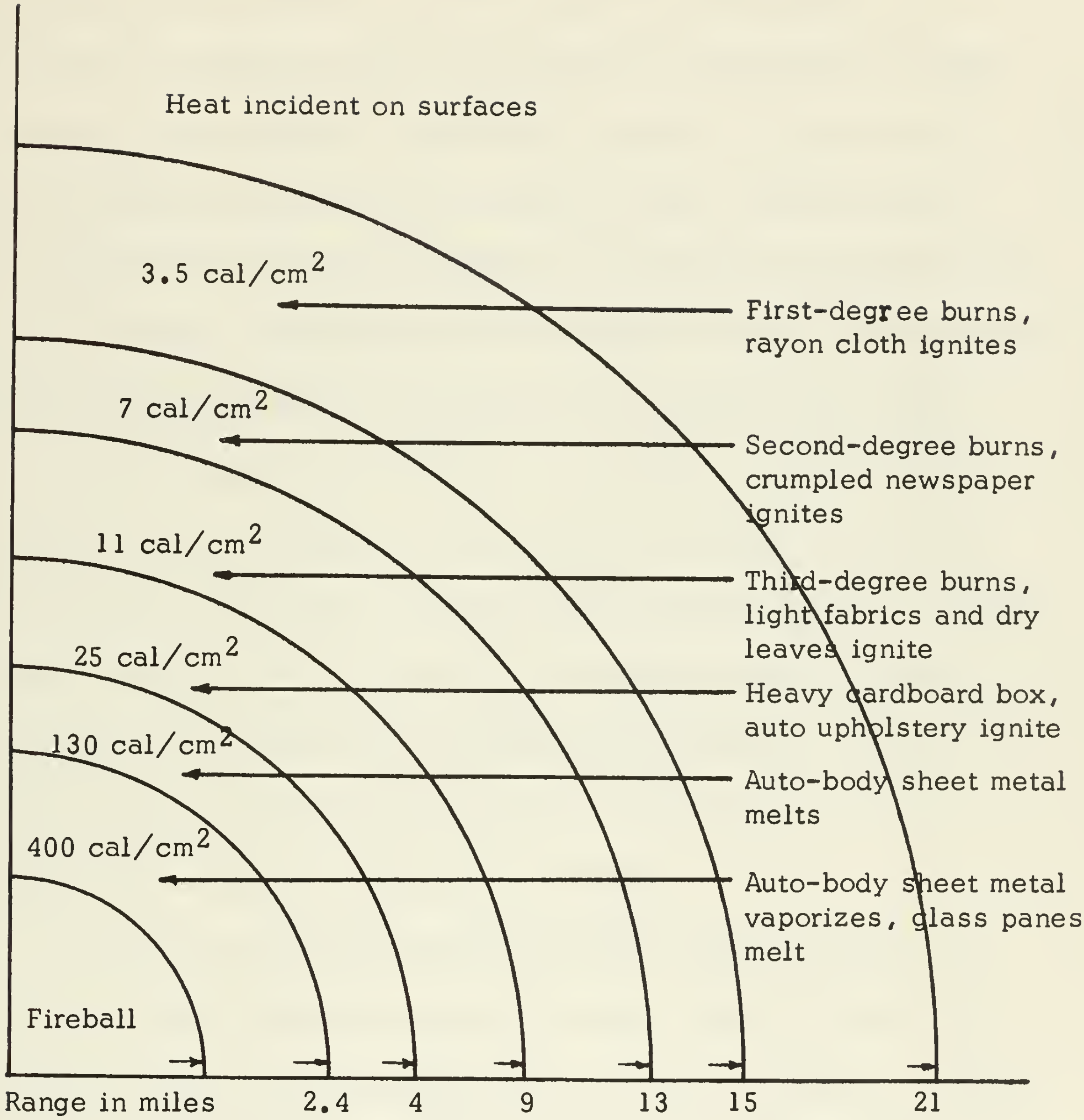

Figure 10. Thermal effects of a 10-megaton surface burst. The above figure shows various levels of heat intensity and the possible effects on materials and personnel in the annular zones between successive range circles.

--Nuclear Attack and Industrial Survival, p. S5.

absorbed, part is reflected, and the remainder is transmitted. It is the amount of radiation which is absorbed which determines the degree of damage to the material. The radiation absorbed, in turn, depends upon the nature of the material and upon its color. A black material will absorb more radiation and suffer more damage than a white material of the same type. The absorbed thermal radiation raises the temperature of the absorbing material at a rapid rate and it is this which causes damage and sometimes the ignition of the material. As the material is exposed to the radiation for only a number of seconds, very little heat conduction takes place, and the heat is concentrated in the surface layers. Because of this, thin or porous materials such as crumpled newspaper or dry, rotted wood, may flame when exposed to thermal radiation; while thick materials, such as wooden boards and heavy fabrics tend to char and smoke but do not burn.

A comparison of the approximate amount of thermal energy per unit area needed to cause the ignition of some common materials can be seen in Table 1. It is interesting to note that a one-megaton weapon needs less thermal energy per unit area than a ten-megaton weapon to ignite the same material. The reason for this is that the effectiveness of thermal radiation increases with the delivery rate. Since the larger weapon has a longer thermal emission pulse than the small one, it must deliver more energy to achieve the same effect.

D. Incendiary effects

There are two general ways in which a nuclear explosion can

TABLE 1

APPROXIMATE RADIANT EXPOSURE FOR IGNITION OF COMMON MATERIALS AND DRY FOREST FUELS

Material	Weight	Ignition exposure (cal/sq cm)		
	oz/sq yd	40 kilotons	1 megaton	10 megatons
Newspaper, shredded	2	4	6	11
Newspaper, dark picture area	2	5	7	12
Newspaper, printed text area	2	6	8	15
Paper, crepe (green)	1	6	9	16
Cotton muslin oiled window shade (green)	8	7	13	19
Paper, Kraft, single sheet (tan)	3	10	13	20
Matches, paper book, blue head exposed		11	14	20
Cotton string scrubbing mop, used (gray)		10	15	21
Excelsior, ponderosa pine (light yellow)	2 lb/cu ft	*	23	23
Cotton string mop weathered (cream)		10	19	26
Rayon gabardine (black)	6	9	20	26
Cotton heavy draperies (dark colors)	13	15	18	34
Paper, Kraft, carton, flat side, used (brown)	16	16	20	40
Paper, bristol board, 3 ply (dark)	10	16	20	40
Cotton denim, new (blue)	10	12	27	44
Paper, bond, typing, new (white)	2	24	30	50

*Data not available or appropriate scaling not known.

cause fires: first by the ignition of thin, dry, highly combustible materials such as paper, window curtains, and dry grass through absorption of thermal radiation; and second, as a side effect of the blast destruction, due to secondary effects such as electrical short circuits and broken gas lines. The total area over which fires could be started is extensive. On a clear day, a ten-megaton air burst could ignite fires over an area of nearly two million acres.

The two primary factors which govern the development of fires accompanying a nuclear explosion are: first, the number of points at which fires originate (ignition points); and second, the character of the surrounding area. Ignition points are locations of exposed, easily combustible materials such as those mentioned above. The chances that a major fire would start because of thermal flash depends to a great extent upon the number of these ignition points in a particular area. The greater the density of ignition points in an area, the greater the chance that small individual fires might combine into a mass fire. Surveys have been conducted to determine the frequency of exterior ignition points for various areas in a given city.[9] The results of these surveys can be seen in Figure 11.

In addition to the density of ignition points, the probability of a major fire developing in a given area depends on such factors as

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[9] Effects of Nuclear Weapons, op. cit., p. 341.

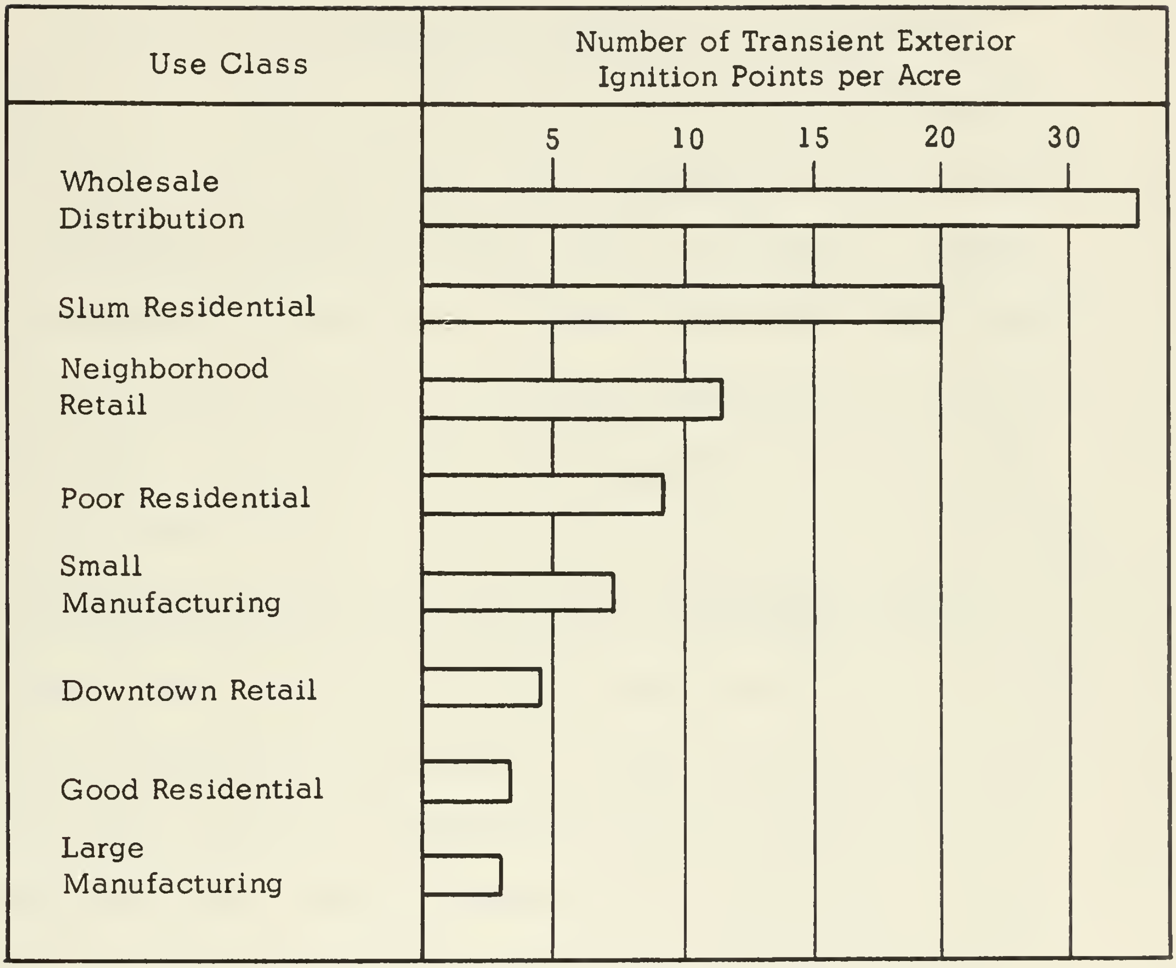

Figure 11. Frequency of exterior ignition points for various areas in a city.

--The Effects of Nuclear Weapons, p. 341.

the weather, the terrain, the spacing between buildings, and the combustibility of buildings.

Major fires are generally classified as one of two types: a firestorm or a conflagration. Firestorms occured in several European cities during World War II as the result of incendiary bombing as well as in Hiroshima following its nuclear attack. A firestorm is probably best described by comparing it to a bonfire. A firestorm, like a bonfire, must have reasonably still air, a sufficient concentration of fuel, and a uniform start, such that the fuel is burning all over at the same time. The rising column of hot air over the fire fans the flame, and draws the surrounding air into the fire, sometimes at a considerable velocity. Extremely high temperatures are created within the firestorm, such that almost everything that can burn does so, often from spontaneous combustion due to the high air temperature, even when untouched by the flames themselves. Although a nuclear attack is practically an ideal match for igniting a firestorm, the requirements for their formation, particularly that of fuel concentration, are such that it is generally believed that chances are small that firestorms would occur in very many American cities.[10]

Although the probability of firestorms following a nuclear attack is small, it is probable that a number of mass fires and conflagrations would occur in various sections of major cities. A conflagration is

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[10]Martin and Latham, op. cit., p. 83.

characterized by a wind-driven burning front which is constantly attacking fresh areas of fuel and leaving behind burnt-out char and ash. Although these fires may be started by nuclear weapons effects, once they have begun they are governed by the same factors which are of concern in conventional fires. The principal difference, which must be considered in preparing defenses against the fires associated with a nuclear attack, is that they are many in number and burning at the same time.

METHODS OF ANALYSIS

Blast Analysis

A. Basic assumptions

The architectural plans submitted in the National School Fallout Design Competition are not detailed, and were developed using codes and construction methods applicable to the various districts from which the designs were submitted. Because of this, it was necessary to make certain assumptions in order to permit comparison of the results of the blast analyses. For example, all analyses were based on a ten megaton surface burst in order to permit comparison of the ranges at which the various nuclear effects would produce specified damage in a given structure. Other assumptions made are as follows:

1. All structural systems must comply with the requirements of either the ACI 318-63 or the AISC 1963 specifications, or both, as appropriate.
2. All structural systems and elements can be idealized as single degree of freedom systems.
3. Loading functions can be idealized in accordance with procedures contained in the Air Force Design Manual.
4. The resistance functions contained in the Air Force

Design Manual can be employed for structural systems and elements as appropriate.

5. Blast analyses are conducted only for those structural elements which are essential to the structure.

6. Certain parameters are assumed to be consistent for all analyses, which include the following:

   a. The depth attenuation factor, $\alpha_z = 1$; i.e., it is assumed that there is insignificant attenuation of vertical pressure with depth in the soil.

   b. The horizontal stress constant, $k = 0.5$. Since negligible information is available on the soil conditions surrounding those structures extending beneath the ground surface, a ratio of horizontal to vertical soil pressure of 0.5 is assumed.

   c. The ductility ratio (or response parameter), $\mu = 1.3$, 3, or 5 depending on the element being analyzed.

   d. The dynamic steel yield strength, $f_{dy} = 50{,}000$ psi.

   e. The dynamic concrete strength, $f'_{dc} = 5{,}000$ psi.

B. Basic procedure

The specific procedure employed in the blast analyses is outlined below.

1. Identify the structural elements and/or systems which are essential to the shelter. These may be broadly classified as:

a. roof and floor systems

b. exterior walls and/or columns

c. interior partitions and/or columns

d. building frames

2. Analyze the elements or systems identified. If required dimensions or details are lacking, determine what would be required for compliance with the appropriate code. The analysis of a given element involves the following steps:

   a. Compute the resistance of element or system, q (or Q), as appropriate.

   b. Compute the period of vibration, T, of element or system.

   c. Prepare the loading function. This step is generally a trial and error process since the peak blast pressure p_m (or P_m) is not known in advance.

   d. Obtain the peak pressure or load, p_m (or P_m), and check against that assumed in step c. If the values agree, proceed to step e.; if not, repeat steps c. and d.

   e. Determine the side-on overpressure (P_{so}) consistent with p_m (or P_m) obtained in step d. above.

   f. Determine range (from a ten megaton surface burst) consistent with the P_{so} obtained in step e. above.

3. Identify the "weak links" in the design and determine what steps might be taken to achieve a "balanced" design.

4. Summarize the analysis.

One of the problems related to the blast analyses is the effect of the "openness" of a building on its blast loading. An "open" structure is one which permits the shock wave to enter, i.e., blast exclusion devices are not provided. In general, the open wall area of the buildings analyzed is less than thirty per cent of the gross wall area and therefore the structures were assumed to be "closed" for purposes of determining loading functions for the structural analyses.[11]

Although the structures were conservatively considered to be closed for purposes of structural analyses, there are some openings in the buildings which would permit the shock wave to enter to some degree. The loading on interior partitions and occupants depends upon the degree to which the shock wave retains its characteristics after entry, which in turn are a function of the size of the opening, the size of the shelter, and the orientation of the opening with respect to the direction of shock propagation.[12] For purposes of determining the loading on interior partitions and occupants it was assumed that the pressure-time function inside would be characterized by a relatively slow rise from the ambient atmospheric pressure to the peak side-on

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[11] N.M. Newmark et al., Air Force Design Manual AFSWC-TDR-62-138 (Kirtland A.F.B., N.M.: U.S. Air Force, December, 1962), p.5-11.

[12] Ibid., p. 5-3.

overpressure existing outside the structure. The overpressure inside was assumed to decay with time as the side-on overpressure outside.

C. Structural deficiencies as designed

In this context, a deficiency is defined as a choice of a structural material, system, or detail which reduces the blast resistance level of the structure below that which could be obtained through a minor change in design at relatively little expense. It is recognized that, had the design competition required consideration of blast resistance, the designers would probably not have selected the material, system, or detail which is criticized.

The most common structural deficiencies in terms of blast resistance were the employment of:

1. concrete block exterior walls
2. concrete block interior partitions
3. concrete block, brick, or stone free-standing radiation shields
4. glass partitions, skylights, or clerestories in the walls or roof adjacent to or over the shelter area.

Non-load-bearing walls of block, brick, or stone have negligible resistance to lateral pressure and should not be used. According to theory and experimental evidence, load-bearing concrete block walls, eight to twelve inches thick and unreinforced, can withstand an incident shock overpressure of only 2 to 3 psi.[13] It is possible

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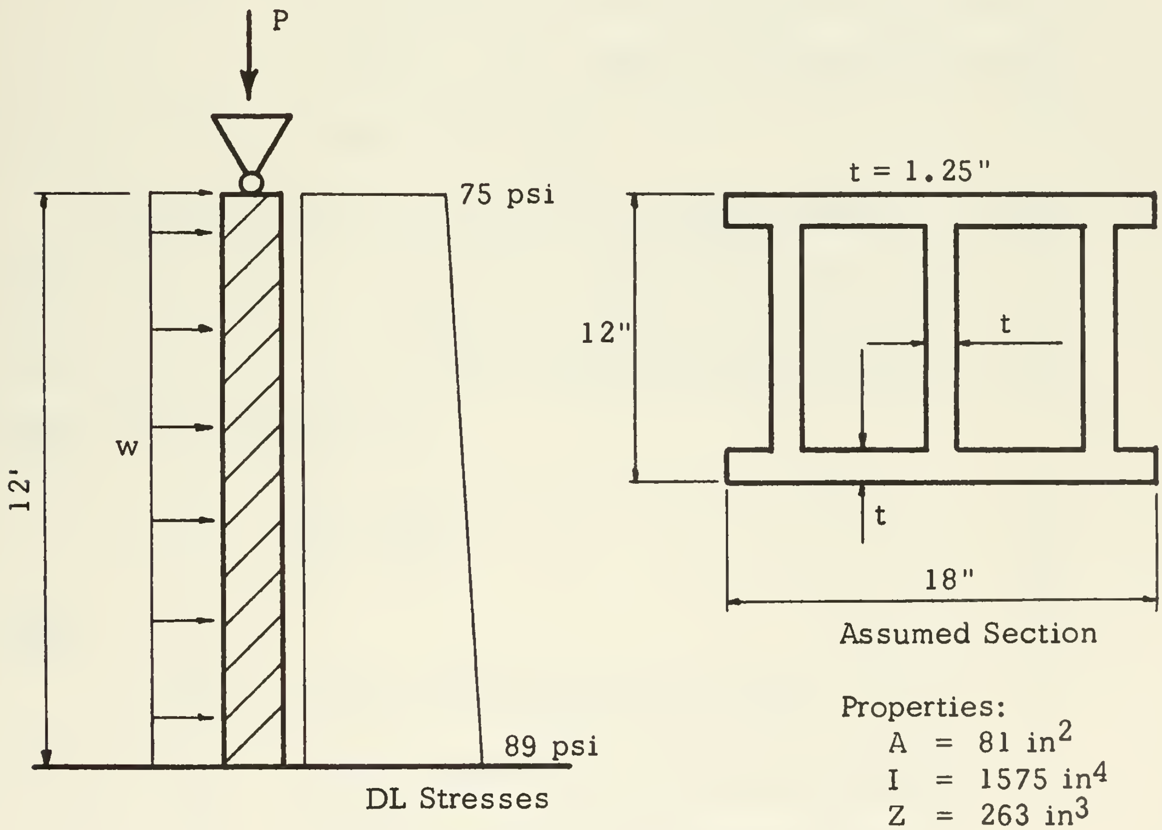
[13] Effects of Nuclear Weapons, *op. cit.*, p. 163.

to increase the resistance of block walls by reinforcing them. However, at this stage, the use of a reinforced concrete wall of the same mass thickness would probably be less expensive. These observations may be seen more clearly in the analysis which follows.

Consider a 12 inch block wall with a mass thickness of about 85 psf. If unreinforced, its resistance to lateral overpressure is determined primarily by the magnitude of the axial stress in the wall (Figure 12).



Properties:
$A = 81\ in^2$
$I = 1575\ in^4$
$Z = 263\ in^3$

Figure 12. Assumptions for analysis of concrete block wall

Under a dead load of 6100 pounds from the roof, the stress in a block at the top of the wall would be 75 psi. The stress in a block at the base, including the weight of the wall, would be 89 psi. Assuming the wall to be hinged at top and bottom, the maximum moment in the wall produced by lateral loading may be expressed as

$$M_{max} = \frac{wL^2}{8} \tag{1}$$

where

M_{max} = the maximum moment produced in the wall

w = the uniform load on the assumed wall section, in this case, 18 p, where p is the lateral pressure

L = height of the wall

Assuming that the block wall has no tensile strength, and that failure occurs when the compressive stress at the extreme fiber has been reduced to zero, the value of lateral pressure required to cause failure may be expressed as

$$p = \frac{8}{18} \times \frac{f_p Z}{L^2} \tag{2}$$

where

p = lateral overpressure on the wall

f_p = extreme fiber stress due to the axial load

Z = section modulus of the assumed section

L = height of the wall

For values of f_p = 89 psi, Z = 263 in.^{3} and L = 144 in.; p = 0.5 psi.

If the roof is subjected to an overpressure level sufficient to raise the stress in the wall to 1800 psi, the wall would be able to withstand a lateral overpressure of 4.5 psi. This corresponds closely to an incident side-on overpressure of about 2 psi before reflection.

It is apparent that vertical reinforcement would further increase the resistance of the wall to lateral pressure. However, a reinforced concrete wall thickness of only 7 inches is required to achieve the same mass thickness. Assuming that the reinforced concrete wall is continuous at top and bottom, and that its height is less than one half its length, the yield resistance of the wall may be expressed as[14]

$$q_f = 0.072\ (\not{p}_c + \not{p}_e)\ f_{dy}\ \left(\frac{d}{L}\right)^2 \qquad (3)$$

where

q_f = flexural resistance of the wall

$\not{p}_c$ = percentage of tensile steel at midspan

$\not{p}_e$ = percentage of tensile steel at the supports

f_{dy} = yield stress of reinforcing steel

d = effective depth of assumed section

L = height of wall

Assuming that the area of tensile steel is 1.5 per cent of the gross cross sectional area of the wall, that f_{dy} = 50,000 psi, d = 5.5 in. and L = 144 in.; then q_f = 15.6 psi.

This resistance, assuming a step pulse and allowing for plastic deformation, corresponds to a reflected overpressure of about 14 psi,

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[14] Air Force Design Manual, op. cit., p. 8-53.

or an incident overpressure of about 6 or 7 psi, depending on the ratio of the stagnation time to the fundamental period of vibration of the wall.

It is possible to design such a wall element to withstand an incident overpressure of 10 psi. It is necessary only to increase the depth of the member or the steel area provided, or both.

The use of a free-standing block, brick or stone wall as a shield is not a feasible solution to the radiation shielding problem if the structure is also to resist any appreciable blast overpressure. The wall would simply no longer be there when it was needed. Also, such walls could act as obstructions to exterior fire fighting operations.

While it is possible to design a reinforced concrete wall which would stand up under overpressures in the range of those which the school structures themselves can withstand, it is more reasonable to incorporate the required mass thickness in the walls of the structure itself.

No analysis is required to establish that as the result of a shock wave flying glass fragments could become a significant missile hazard to shelter occupants. It is possible to protect the occupants from this hazard through such means as heavy drapes or sliding or rotating panels. However, such protection methods rely on design features which require some positive action on the part of the shelter occupants. To be effective, such mechanisms must be maintained so that they are operable at all times, and the shelter occupants must

be trained to close them quickly in an emergency. It is preferable that this type of protection should be of passive rather than active nature, an example being the use of baffles. Baffling has the added advantage of offering protection from thermal radiation, and this concept is used successfully in several of the school designs.

Thermal Analysis

A. Basic assumptions

The architectural plans which are the basis of this investigation were developed using fire and building codes applicable to the various districts from which the designs were submitted. In order to maintain continuity in this study, it was necessary that certain generalizations and assumptions be made. As an example, the principal references used for all analyses were the National Building Code, recommended by the National Board of Fire Underwriters (New York: 1955) and the Fire Protection Handbook, ed. G.H. Tryon (12th ed.; Boston: National Fire Protection Association). Other references consulted are listed in the bibliography.

Since the plans were not detailed, certain design assumptions were made as required for analysis. These assumptions dealt with such matters as room contents, window details, and specific items relevant to the building being analyzed. Assumptions made which are applicable to all buildings are as follows:

1. The sequence of events following a nuclear attack is

(1) thermal radiation, (2) blast effects, with the possibility of secondary fires, (3) radioactive fallout, and simultaneous hazard to the shelter from exposure fires. These events are sequential and separated by an interval of time.

2. The major fire-fighting effort will take place between the time of the blast effects and the arrival of radioactive fallout.

3. There will be no fire storm following the attack, but fires will be widespread and numerous.

4. All structures conform to Section 703, Fire Resistive Construction Type B (NBFU). Noncombustible construction is acceptable, but fire resistive construction is preferred.

5. The fire load[15] for the fire resistive building will approximate 5 psf with an assumed heat potential of 40,000 BTU/sq. ft. (contents, finished flooring, interior finish and trim) and an equivalent fire rating of thirty minutes. This fire load does not hold for hazardous areas,[16] where it is variable.

6. Practical assumptions are made in cases not covered by present codes (e.g., underground educational spaces).

7. With the exception of windowless and underground buildings,

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[15]The fire load is the weight of combustible materials per square foot of floor area.

[16]Hazardous areas are those of greater than normal fire load, or those where ignition of fires is most likely to take place.

smoke venting will be provided primarily by doors and windows.

In the event of a nuclear attack, fallout shelters would be threatened by fires which can be placed in three basic categories: First, fires resulting from ignition by direct thermal radiation from the nuclear blast; second, fires resulting from exposure to flames in the surrounding area; third, fires initiating within the shelter, as a result of either blast damage or accidental ignition.

B. Criteria to resist direct thermal ignition

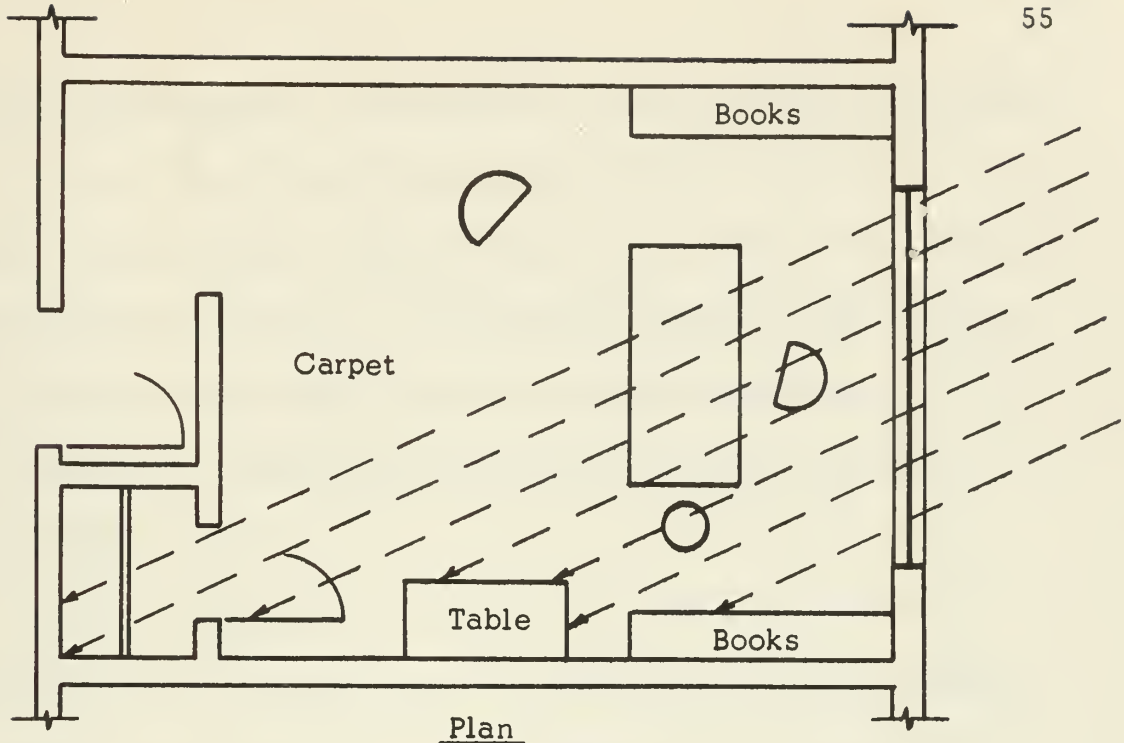
Although the approximate amount of thermal energy required for the ignition of certain specific materials has been established, the wide range of materials and conditions which could be involved permits only a qualitative appraisal of the thermal ignition problem. Whether a combustible material will ignite and continue to burn after exposure to thermal energy resulting from a nuclear explosion is dependent on a number of factors, of which the thickness and color of the material are predominant. As the line-of-sight thermal rays are attenuated by solid noncombustible materials, the most obvious means of protection from thermal radiation is through the use of barriers and the selection of noncombustible materials for furnishings and construction.

In the analysis of the plans, interior areas opposite windows have been carefully examined with the thermal rays coming from any point where screening is not provided. It has been determined that

prevention of ignition to the interior of the building is a function of the exposed materials and the size, shape, and location of the exterior openings. Rays sketched on the plan and elevation views where openings appear indicate the extent to which the interior of the structure is exposed to thermal radiation. Exterior walls of fire resistive construction are not affected by thermal rays.

Figure 13 illustrates a typical room situation with windows to the outside and a door on the opposite wall. It can be seen that thermal radiation could impinge on almost all parts of the room. Ignition could take place in the carpeting, furniture, paper and other room furnishings. The thermal resistance of this room could be improved through the use of barriers to limit the amount of thermal radiation entering the room, and by substitution of noncombustible materials where possible. The use of barriers can be incorporated in a number of ways, and is essentially a function of the architectural design. Raising the sill height and extending projections over the windows are most effective from this standpoint without recourse to actual removal of the window. The use of drapes can also be quite effective, and they should be of relatively heavy material which is preferably noncombustible. Combustible drapes should be wetted down prior to exposure, which will cause the thermal energy to be dissipated in heating the water in the drapery material.

To remove or eliminate the ignition points attention is primarily focused on thin materials. Included are paper, chair upholstery fabrics,



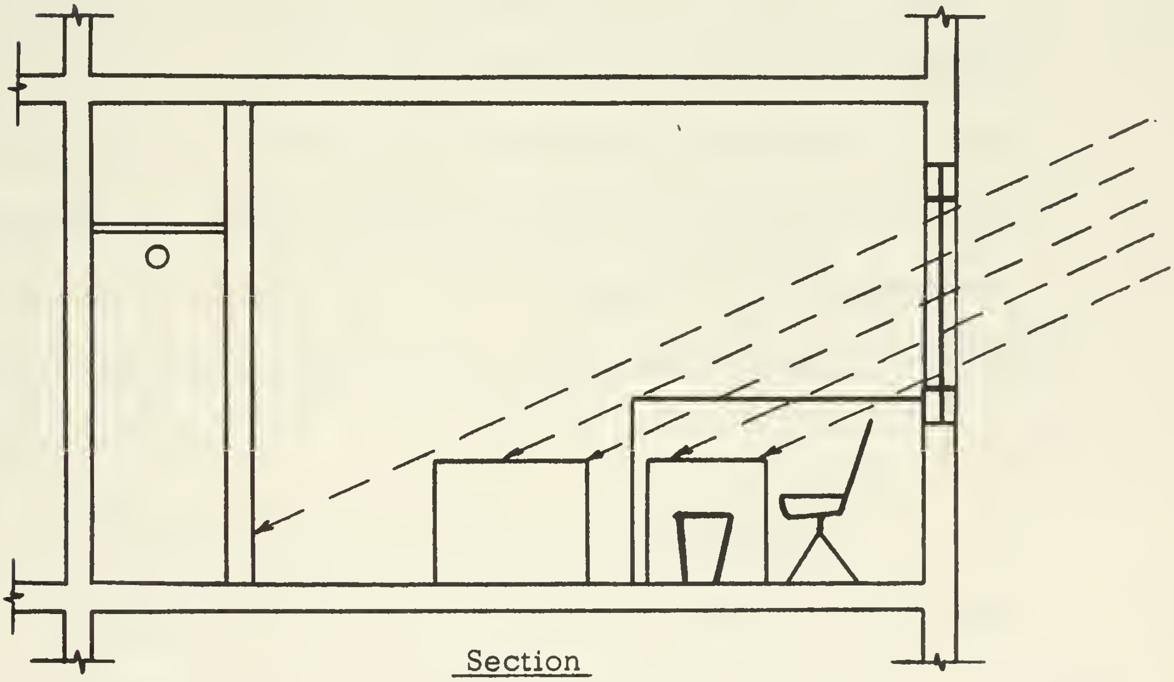


Figure 13. Combustible Material in Room

Panelled Walls of 1/4" Veneer
Carpeting
Wood Window Frames
Books and Book Cases
Chairs
Desk and Table
Waste Paper
Curtains
Painted Surfaces
Contents of Closet

curtains, and carpeting. It is desirable to limit all combustible material in the room as well as that which is easily ignited and acts as a "match" or ignition point. Heavy drapes, as mentioned above, may be substituted for the curtains. A noncombustible carpet, substitution of metal for wood in the window frames, and an alternate treatment of the walls of the room to eliminate the veneer will materially reduce the fire load in the room.

Should it happen that the contents of the room ignite due to thermal impingement the fire must be contained and self-help measures employed to combat the fire, or, in the absence of fire fighting, the fire should burn out without endangering the rest of the building. Of principal concern in this regard is the door opening to the remainder of the building. The required fire resistance of the door, as well as the partitions, is based on the fire load in the room. Assuming that the fire load of this room is 5 psf, all elements of the compartment with the exception of the windows should have a minimum fire rating[17] of half an hour.

C. Criteria to resist ignition from exposure fires

The factors which affect ignition of the interior of a building, or the structure itself, are similar whether the source of heat is thermal radiation from a nuclear explosion, or an adjacent burning structure which may have been ignited by thermal radiation or blast effects.

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[17] The fire rating is an arbitrary indication of fire resistance measured in hours.

The major difference lies in the delivery rate of the thermal energy. The transfer of heat by an exposure fire is sustained over a relatively extended period of time, while the thermal flux attending a nuclear blast, although more intense, is transmitted in a number of seconds.

Ignition of an exposed building depends on such factors as the temperature of the exposing fire, the total heat produced, the atmospheric conditions, the wind velocity and direction, the type of construction, the protection of openings, and the proximity and extent of the exterior fire with respect to the exposed building. Firebrands are an additional hazard, but lack of data makes it difficult to assess their effects. This hazard can be limited through use of fire resistive roof construction.

Energy is transported from exposure fires through radiation, and in some cases, convection. Procedures have been developed which permit good quantitative estimates of the possible hazard to a building due to the transfer of energy from exposure fires by radiation. The factors affecting convective heat transfer, however, are subject to greater variations than those of the radiation mode and require treatment of a more qualitative nature. Where the relationship between structures is such that the exposed building is above the exposing building and convective heat transfer could be serious, experience and judgment must be exercised in the absence of a quantitative solution to the problem.

The amount of radiation energy arriving at a point of an exposed structure due to the proximity of an exposure fire is known as the ex-

posure severity index (E_e) and is measured in terms of hours. The exposure severity is dependent on the solid angle subtended at a point by the flames and on the emissive power of the flames. The solid angle measures the field of view of a detector occupied by the radiating surface. The "shape factor" (F) is the solid angle expressed as a percentage of the field of view and is used in calculations concerned with heat radiation from exposure fires. The emissive power of a fire is measured in terms of the amount, type, and distribution of available fuel, and is termed the fire load index (q_e) with units of pounds per square foot.

The basis in establishing a combustion criterion for a building exposed to heat radiation is the relationship between the exposure fire load and the exposure severity. The equation for exposure severity is:

$$E_e = F(0.10 q_e) \qquad 0 < q_e \leq 30 \text{ psf} \qquad (4)$$

$$E_e = F(0.15 q_e) \qquad q_e > 30 \text{ psf} \qquad (5)$$

where

E_e = exposure severity index in hours

F = shape factor

q_e = exterior fire load index, psf

When E_e has been calculated for a particular exposure fire situation, it can be compared to the fire resistance rating of various building materials (Table 2) and therefore serve as an ignition criterion for the exposed building.

The principal heat sources in considering exposure fires fall into four categories: (1) Flammable liquid exposure; (2) Combustibles in the surrounding yard areas; (3) Walls of adjacent buildings; and (4) Roofs of adjacent buildings.

Gas or liquid storage tanks may rupture when subject to the blast effects of a nuclear explosion, or they may become a fire hazard in some other way. In the case of storage tanks, parameters concerning the size of the fire area are difficult to determine after a tank has ruptured, making exposure fire calculations difficult. Tanks should be separated from other installations by a distance which varies with the size of the tank. The ground should slope away from buildings housing shelters, especially in the case of underground or basement shelters. The separation distances shown below should be sufficient under normal conditions.[18]

Size of Tank (thousands of gallons)	Separation Distance (feet)
10	100
20	130
50	200
100	260
500	600

[18] "Fire Safety to Life, Classification Guide for Fallout Shelters" OCD-PS-64-40 (unpublished report by the Factory Mutual Research Corporation, Norwood, Mass.).

As the exposure severity index (E_e) depends on the exposure potential of the surrounding yard areas, the walls of adjacent buildings, and the roofs of adjacent buildings, the contribution of each of these sources is calculated separately with the summation of these three being the total exposure severity index which serves as the combustion criterion for a building exposed to heat radiation.

Calculation of the Exposure Load Index (q_e)

The exposure potential of combustibles stored in an adjacent yard depends upon the amount and the type of combustibles, as well as the manner in which they are stored. The relationship of these various factors is described by the equation:

$$q_{ey} = (HF)\,(SF)\,(w_{ey}) \qquad (6)$$

where

q_{ey} = Exposure load index for yard storage, psf

HF = Heat factor, wood equivalent (Table 4)

SF = Storage factor (Table 5)

w_{ey} = Weight of combustible material, psf of yard

The exposure potential of an adjacent exposing building depends on the total weight of combustibles in the building, including any combustible portion of the building itself. It is assumed that the fire is uniformly distributed throughout the building, with the roof and walls considered as uniformly radiating surfaces. Dividing the weight of combustible material by the surface area of the building

(exterior walls and roof) decides the exposure load (w_{eb}).

As an example of calculating the exposure load consider a building 100 feet by 200 feet in plan and 32 feet high containing 400,000 pounds of combustible materials. This building would have an exposure load of 400,000/(100 x 200 + 32 x 600) = 10 psf.

In determining the exposure load index of an exposing building with a given exposure load, the fire resistance of its roof and walls, the number of openings in the exterior walls, and the average wood equivalent of its combustible materials are taken into account. The governing equation is:

$$q_{eb} = (RWF)(HF)(w_{eb}) \qquad (7)$$

where

q_{eb} = Exposure load index for exposing building, psf

RWF = Roof and wall factor (Table 9)

HF = Heat factor (average wood equivalent of exposing building and contents, from Table 4)

w_{eb} = Weight of combustible material, psf of building surface

It may be seen that the adjustment factor does not reduce the exposure in direct proportion to the percentage of opernings. This is accounted for by the spread of flames from the openings.

Buildings which extend above the exposure building are subject to hot gasses which are forced upward from the burning building. The factors for roofs which appear in Table 9 have been arbitrarily doubled

which should result in a reasonable separation severity relationship based on fire protection experience.

Calculation of the Shape Factor (F)

The shape factor is used to describe conveniently the separation and size of the exposing fire. It is essentially a measure of the degree to which the field of view of a detector is occupied by the radiating surface.

As illustrated in Figure 14, structure A, the exposed building, receives energy from structure B and the adjacent storage yard. The maximum incident heat flux on the exterior wall of structure A is evaluated by use of the shape factor for any desired height, h_a. Referring to the plan view, the shape factor will be a maximum at the point where the extension of the center line of the exposing surface intersects the exterior wall of building A. Equations are given for the shape factor from h_a to the yard, roof, and facing exterior wall of structure B.

The storage yard shape factor is defined as:

$$F_y = F_{(d_1 + d_2)} - F_{d_2} \quad (8)$$

where

$$F_{(d_1 + d_2)} = f(N_1, L) \quad (9)$$

$$F_{d_2} = f(N_2, L) \quad (10)$$

The shape factors F_{d_1} and F_{d_2} are read from Table 7. The parameters needed to enter the table are calculated as shown below, using information obtained from Figure 14.

$$N_1 = (d_1 + d_2)/W_y \tag{11}$$

$$N_2 = d_2/W_y \tag{12}$$

$$L = h_a/W_y \tag{13}$$

The roof shape factor, used to evaluate the exposure to the floors of the exposed building which are above the roof of the exposure building is:

$$F_r = F_{(d_o + d_b)} - F_{d_o} \tag{14}$$

where

$$F_{(d_o + d_b)} = f(N_1', L') \tag{15}$$

$$F_{d_o} = f(N_2', L') \tag{16}$$

The shape factors $F_{(d_o + d_b)}$ and F_{d_o} are read from Table 7. The needed parameters are calculated as shown below, using information obtained from Figure 14:

$$N_1' = (d_o + d_b)/W_b \tag{17}$$

$$N_2' = d_o/W_b \tag{18}$$

$$L' = (h_a - H_b)/W_b \tag{19}$$

The method for obtaining the shape factor for adjacent walls is divided into two cases. Case 1 is used when h_a is less than H_b and case 2 is used when h_a is greater than H_b (Figure 14).

Case 1, h_a less than H_b:

$$F_w = F_1 + F_2 \tag{20}$$

where

$$F_1 = f(X_1 Y_1) \qquad F_1 = O \text{ for } h_a = O \tag{21}$$

$$F_2 = f(X_1 Y_2) \qquad F_2 = 0 \text{ for } h_a = H_b \tag{22}$$

The shape factors F_1 and F_2 are read from Table 8. The needed parameters are calculated as shown below, using information obtained from Figure 14.

$$X_1 = W_b/d_o \tag{23}$$

$$Y_1 = h_a/d_o \tag{24}$$

$$Y_2 = (H_b - h_a)/d_o \tag{25}$$

Case 2, h_a greater than H_b:

$$F_w = F_1 - F_2 \tag{26}$$

where the shape factors F_1 and F_2 are calculated in the same manner as in case 1.

The equations listed above permit calculation of the approximate total exposure severity to which a building could be subjected. This result can be used as a criterion for estimating the structural fire resistance required of a building to prevent ignition by exposure fires.

D. Criteria to resist interior fires

The amount, type, method of storage, and distribution of combustibles are the principal influences which determine the interior fire hazard to a building. In order to arrive at some value for fire resistance, the fire potential and its relationship to the expected fire severity must be considered.

In order to determine the expected fire severity, it is necessary to develop a fire load for each area being considered. Contents of a

building are seldom distributed uniformly over a floor area, and the fire duration and intensity in an area, which is based on the average fire load, may be much higher than expected due to concentration of the combustibles. Some basic rules which aid in minimizing this effect are the following:

1. If the fire load over a floor area of 10 square feet does not exceed twice the average and the contents are reasonably distributed, the average fire load can be used.
2. When less than 10 per cent of the floor area is loaded to less than three times the remainder, the average fire load can be used.
3. When more than 60 per cent of the fire area is covered with a higher load, the higher load should be used rather than the average.

The relationship which exists between fire load and fire severity has been established for fire resistive structures with combustibles having a calorific value in the range of wood and paper. The probable duration and intensity of the resulting fire are graphically presented in Figure 15 and Figure 16, respectively.

The adjusted fire load, or the fire load index, is calculated using the following equation:

$$q = (w)(HF)(SF) \tag{27}$$

where

q = Interior fire load index, psf

w = Weight of combustible material, psf of floor area

HF = Heat factor (Table 4)

SF = Storage factor (Table 5)

The fire load index is converted to the fire severity by use of Figure 15. Figure 15 was developed from results of test fires in fire resistive structures using wood and paper for combustibles, and may be somewhat inaccurate for certain types of combustibles, although the introduction of heat and storage factors to modify the fire load makes use of the figure reasonable.

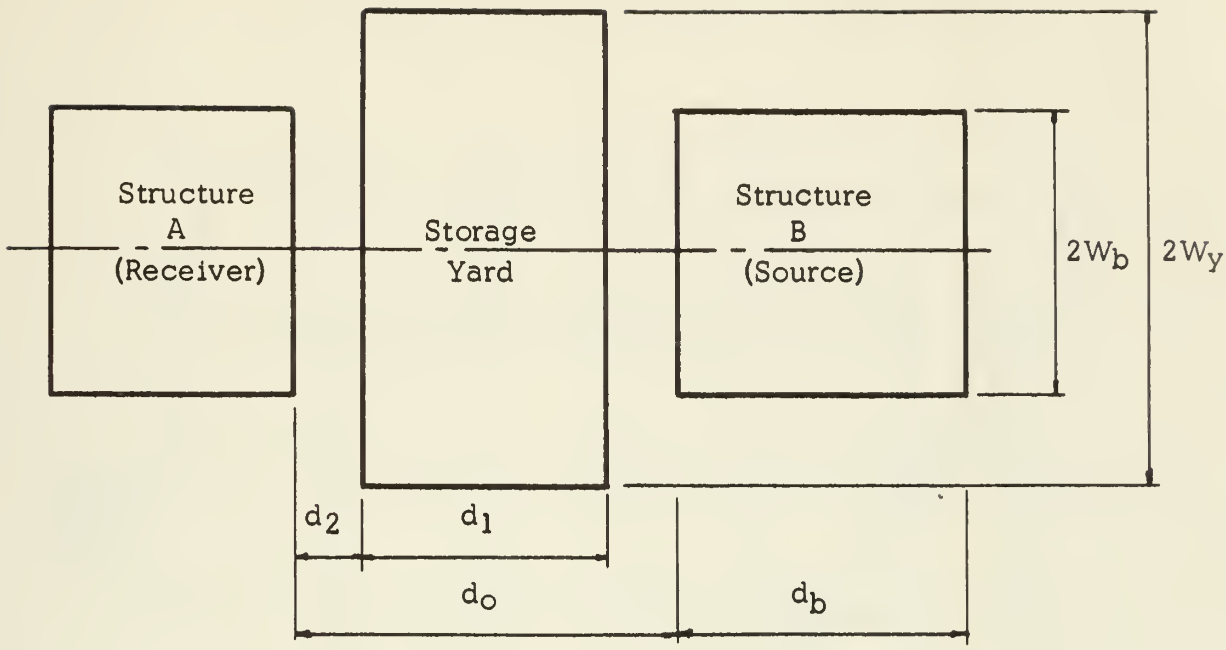
The fire severity calculated should be rounded off to the nearest half hour when greater than one hour, and to the nearest quarter hour when less than one hour. The fire severity index represents an estimate of the structural fire resistance required of the building elements to prevent the disastrous spreading of interior fires.

Radiation Analysis

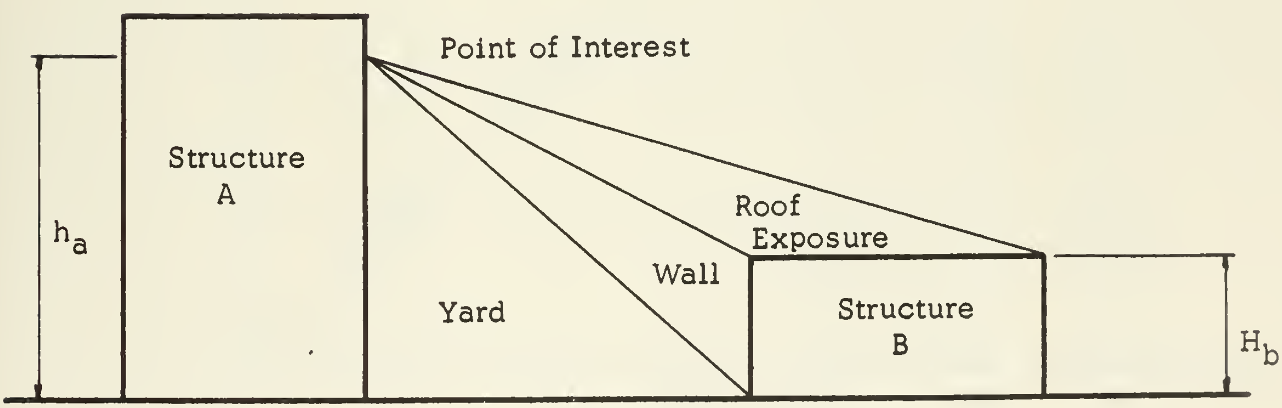
One of the criteria of the National School Fallout Shelter Design Competition was that all schools should be designed to provide a protection factor of at least 100. This protection factor was incorporated into the designs by methods established in Office of Civil Defense Publications, Guide for Architects and Engineers, or Design and Review of Structures for Protection from Fallout Gamma Radiation.

Thus there was no need to conduct a radiation protection analysis of the schools as they were presented.

Where design changes were recommended to improve a specific school's resistance to integrated nuclear weapons effects, analyses were conducted to determine if any significant changes in protection factor would result. These analyses were conducted using the Protection Factor Estimator TM 64-1, May 1964, published by the Department of Defense, Office of Civil Defense, Washington 25, D.C.



Plan View



Elevation View

Figure 14. Location of External Exposure

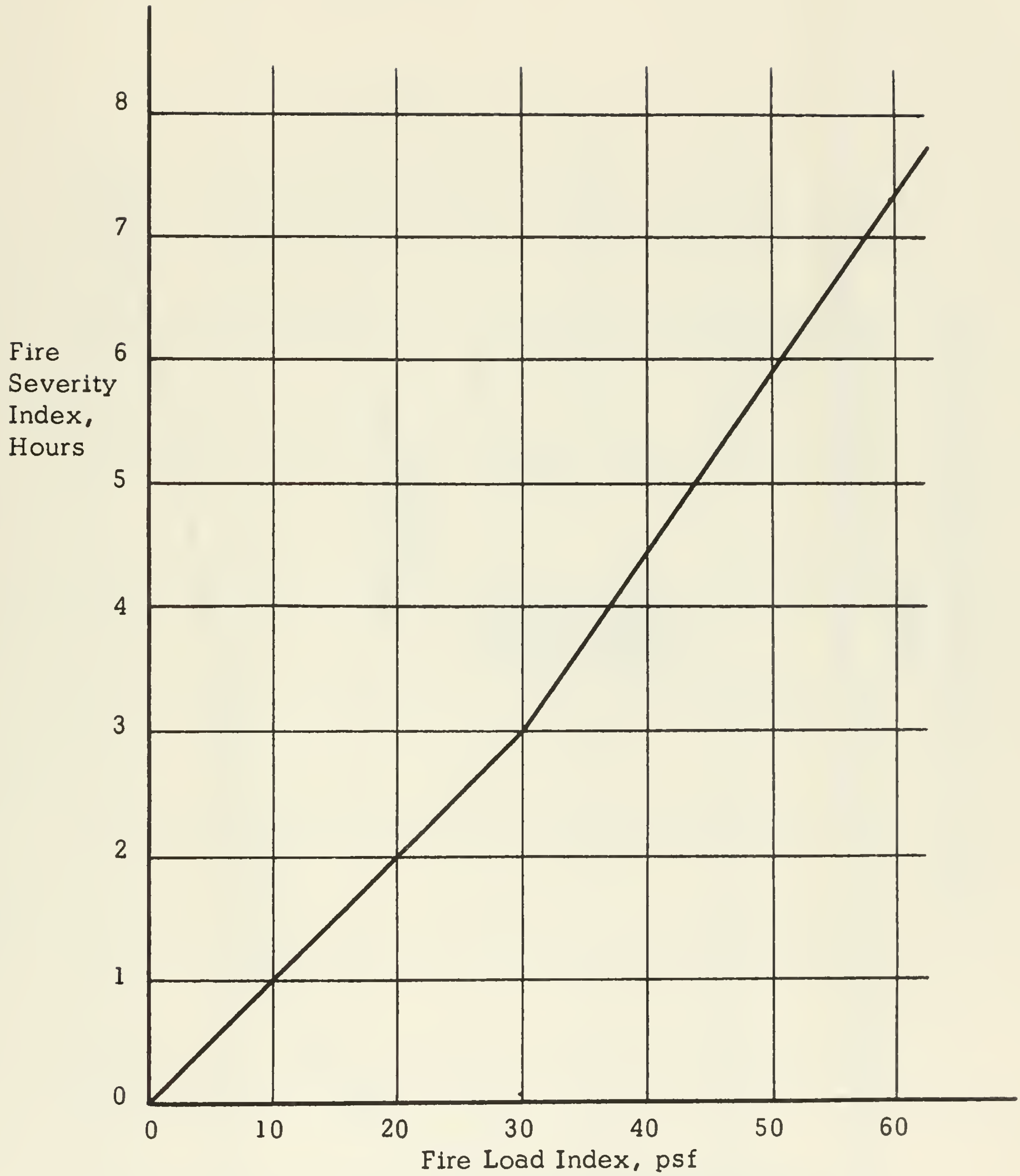


Figure 15. Relationship of Fire Load to Fire Severity

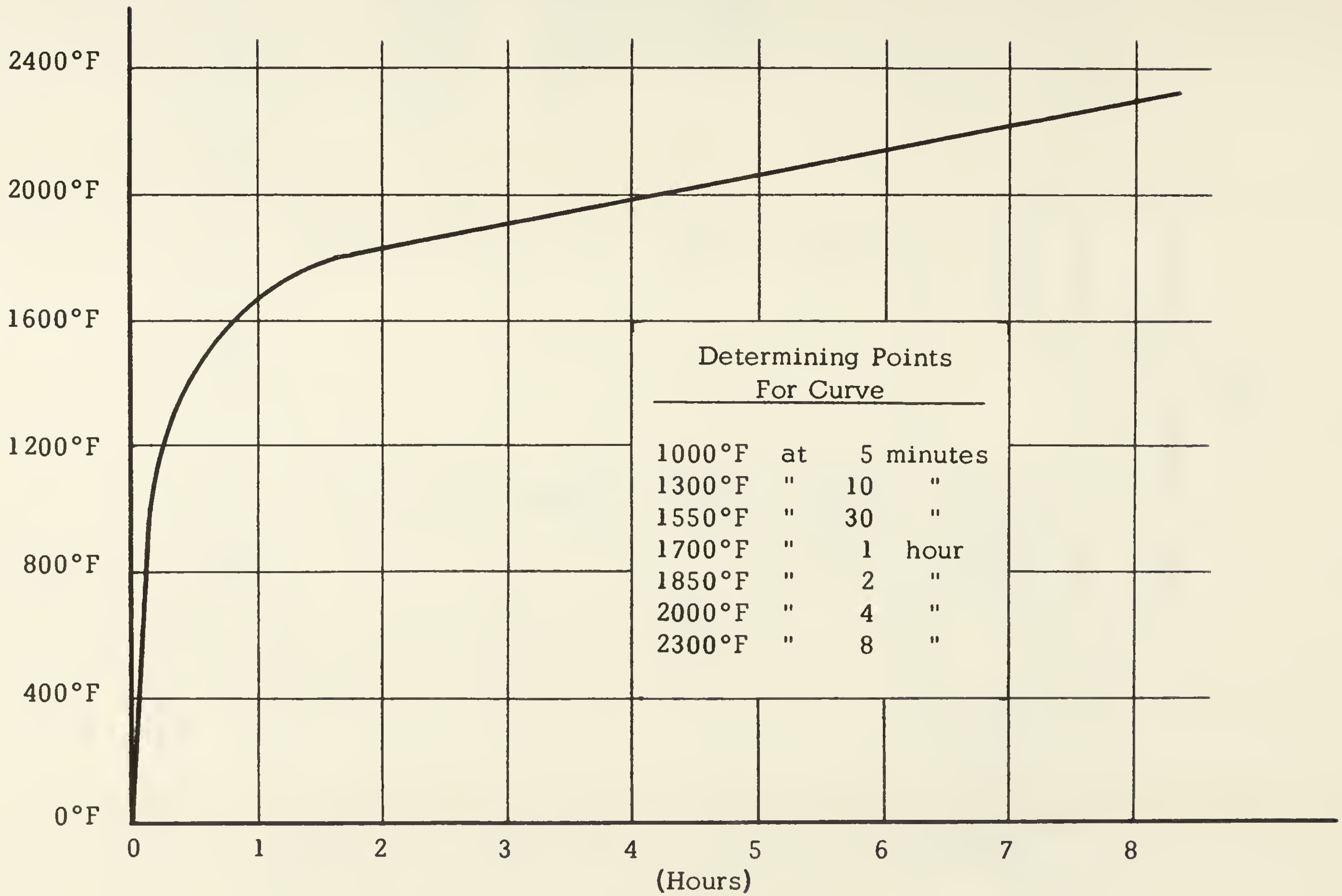


Figure 16. Standard Time-Temperature Curve

TABLE 2

LOAD-BEARING MASONRY WALLS

Material	Wall Thickness Inches	Solid Content of Walls Per Cent	Fire Resistance Rating - Hours (No Plaster)
Brick	12	90-100	10
	8	90-100	5
	4**	90-100	1
Reinforced Concrete	8	100	5
	6	100	3
	4**	100	1
Load-Bearing Hollow Tile (Not Partition Tile)	12	45	3
	8	48	2 1/2
	8	40	2
	6**	40	3/4
Concrete Block, Cinder or Stone Aggregate***	12	62	8
	8	74	4
	8	64	3
	8	58	2
	6**	62	1 1/2

** Nonload-bearing wall restrained on all edges.

*** Stone aggregate containing less than 65% silica, chert or flint.

TABLE 3

RELATION OF FIRE LOAD TO FIRE SEVERITY

Average Weight of Combustibles, psf of Floor Area*	Fire Severity, hrs of Standard Time-Temperature Curve
5	1/2
10	1
15	1 1/2
20	2
30	3
40	4 1/2
50	6
60	7 1/2

*Data applies to fire resistive structures with combustibles having a calorific value in the range of wood and paper (including combustible furniture and shelving, and finish floor and trim)

TABLE 4

HEAT FACTOR

Substance	Btu/lb	Wood Equivalent
Wood, Cellulose	8000	1.0
Paper	7200	0.9
Coal	14000	1.8
Coke, Charcoal	12000	1.5
Lignite	6500	0.8
Peat	10000	1.3
Straw, Hay	6200	0.8
Petroleum Products	20000	2.5
Coal Tar, Asphalt, Bitumen	17000	2.1
Fats, Wages	17000	2.1
Animal, Vegetable Oil	17000	2.1
Silk	9200	1.2
Wool	9200	1.2
Cotton	7100	0.9
Nitrocellulose	4 200	0.5
Rubber	17000	2.1

TABLE 5

STORAGE FACTOR

Substance	Loose, In Piles, Low Density, Large Surface	Piled in Sacks or Barrels, Average Density, Average Surface	Compact, in Bales, High Density, Small Surface
Wood and Wood Products	1.4	1.0	0.5
Paper	1.7	1.2	0.6
Coke	0.8	0.3	0.2
Coal	1.0	0.6	0.4
Peat, Charcoal	0.8	0.6	0.5
Silk	1.4	0.9	0.6
Cotton	1.2	0.8	0.5
Wool	0.8	0.6	0.4
Rubber, Plastics	1.3	1.0	0.7
Nitrcellulose Celluloid	4.0	3.0	2.0
Grain	1.0	0.8	0.6
Flour	0.9	0.7	0.5
Hay and Straw	1.8	1.3	0.9

TABLE 6

EFFECTIVE COMBUSTIBLE CONTENTS OF STEEL CONTAINERS

	Part of Combustibles in Containers		
Type of Container	Less Than One-Half	One-Half to Three-Fourths	More Than Three-Fourths
No Containers	1.00	1.00	1.00
Backed and Partitioned Shelving	0.75	0.75	0.75
Shelving With Doors and Transfer Cases	0.60	0.50	0.25
Filing Cabinets and Desks	0.40	0.20	0.10
Safes and Cabinets of 1-hour or More Fire-Resistance Rating	0.00	0.00	0.00

TABLE 7

TABLE OF SHAPE FACTORS FOR EXPOSURE BY ADJACENT YARD OR ROOF FIRE

L/N	0.05	0.1	0.2	0.4	0.6	1.0	2.0	4.0	6.0	10.0	20.0	
0.00	.50	.50	.50	.50	.50	.50	.50	.50	.50	.50	.50	.50
0.02	.31	.40	.45	.47	.48	.49	.49	.49	.49	.49	.49	.49
0.05	.15	.28	.38	.44	.46	.47	.48	.48	.48	.48	.48	.48
0.10	.05	.15	.27	.38	.41	.44	.46	.47	.47	.47	.47	.47
0.2	.01	.05	.15	.27	.34	.37	.42	.43	.44	.44	.44	.44
0.4		.01	.05	.14	.21	.35	.37	.38	.38	.38	.38	.38
0.6		.01	.02	.08	.13	.21	.29	.31	.32	.33	.33	.33
1.0			.01	.03	.06	.11	.19	.23	.24	.25	.25	.25
2.0				.01	.01	.02	.07	.12	.13	.14	.15	.15
4.0							.02	.04	.05	.07	.07	.08
6.0							.01	.02	.03	.04	.05	.05
10.0									.01	.02	.03	.03
20.0											.01	.02

TABLE 8

TABLE OF SHAPE FACTORS FOR EXPOSURE BY ADJACENT WALL FIRE

X/Y	0.0	0.1	0.2	0.4	0.6	1.0	2.0	4.0	6.0	10.0	20.0	
0.1	.00	.01	.01	.02	.03	.04	.05	.05	.05	.05	.05	.05
0.2	.00	.01	.02	.05	.06	.08	.09	.10	.10	.10	.10	.10
0.4	.00	.02	.05	.08	.11	.15	.18	.18	.19	.19	.19	.19
0.6	.00	.03	.06	.11	.15	.21	.25	.25	.26	.26	.26	.26
1.0	.00	.04	.08	.15	.21	.28	.33	.35	.35	.35	.35	.35
2.0	.00	.05	.10	.18	.25	.33	.41	.44	.44	.45	.45	.45
4.0	.00	.05	.10	.18	.25	.35	.44	.47	.48	.48	.48	.49
6.0	.00	.05	.10	.19	.26	.35	.44	.48	.49	.49	.49	.49
10.0	.00	.05	.10	.19	.26	.35	.45	.48	.49	.50	.50	.50
20.0	.00	.05	.10	.19	.26	.35	.45	.48	.49	.50	.50	.50
∞	.00	.05	.10	.19	.26	.35	.45	.49	.49	.50	.50	.50

TABLE 9

ROOF AND WALL FACTOR

Exposure Description	Factor (RWF)	
Fire Resistive Construction	Wall	Roof
No Openings	0.0	0.0
10% Openings	0.3	0.6
30% Openings	0.7	1.4
50% Openings	1.0	2.0
Combustible Construction	1.0	2.0

TYPICAL EVALUATION

In order to illustrate the methods of analysis described in the previous chapter a typical evaluation of one of the designs of the National School Fallout Shelter Design Competition is presented. The chosen design for the sample evaluation is the second prize winner from Region 7. The elevation and plan views are shown in Figures 17 and 18, respectively.

Blast Evaluation

This design employs a core-type shelter, in which the classrooms surround the shelter area. The structure consists essentially of a reinforced concrete roof system supported by brick bearing walls on the perimeter and by a system of brick bearing walls, reinforced beams, and columns in the interior. For the purposes of this analysis it is assumed that only the core shelter area need be designed to withstand blast overpressure. This assumption will result in leaving the exterior architectural treatment essentially unchanged. The grouted brick walls which are specified in this design have very low resistance to blast overpressures, and they must be redesigned using reinforced concrete construction in order to achieve a significant degree of blast resistance. It is recommended that the interior partitions not be of metal stud and

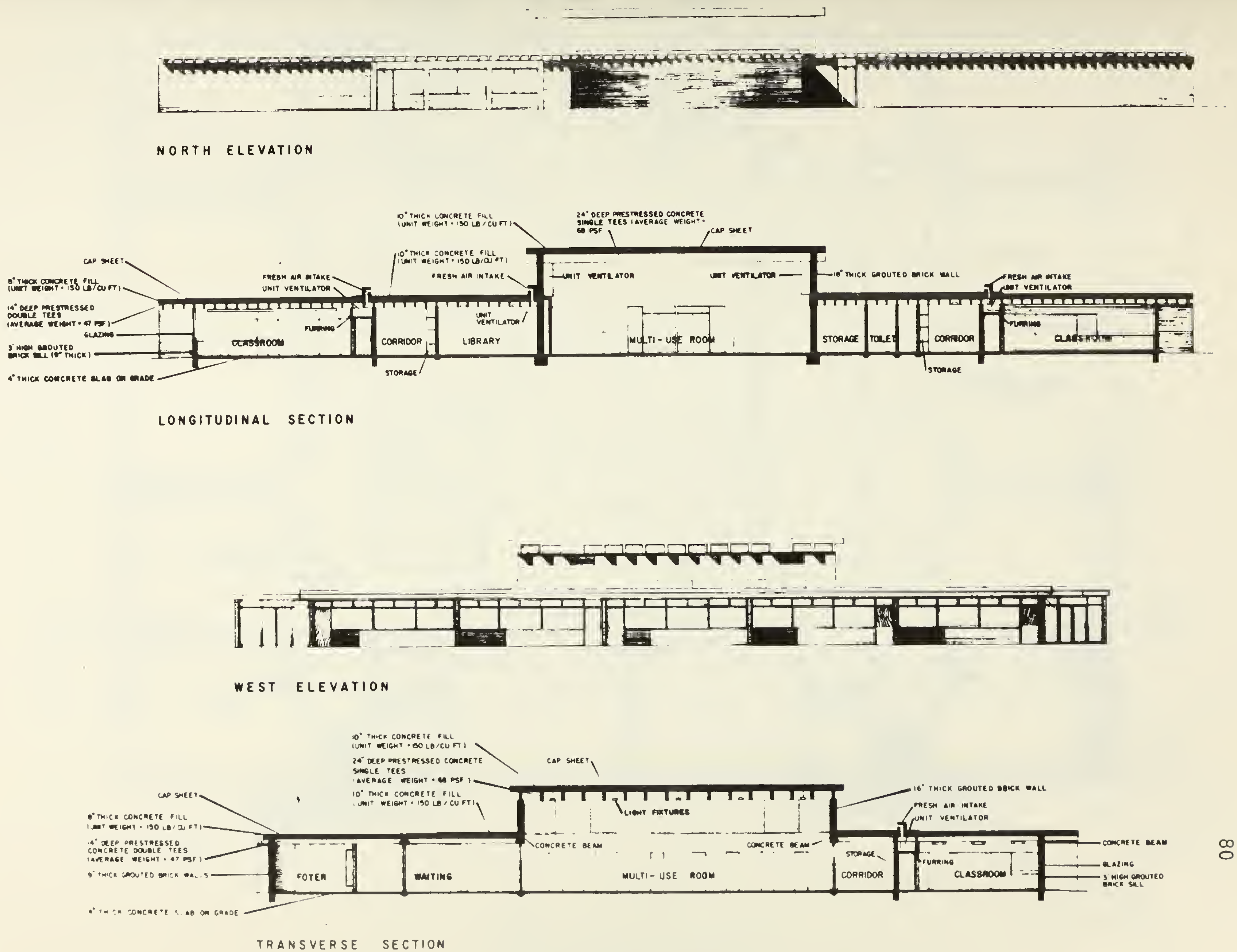


Figure 17 Elevation views of structure used in typical evaluation

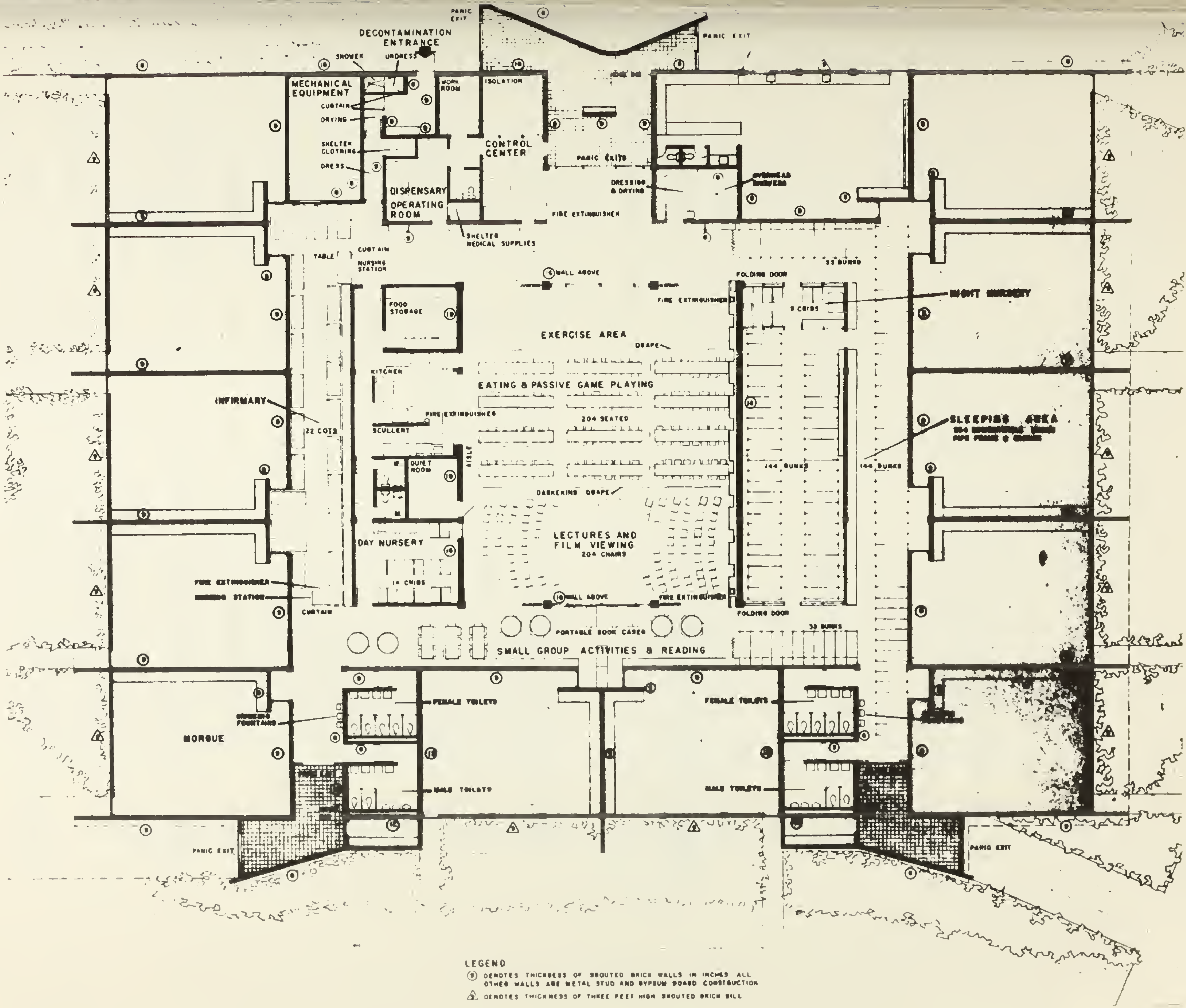


Figure 18 Plan view of structure used in typical evaluation

gypsum board as shown in the drawings.

The procedure employed in the blast evaluation is that outlined in the previous chapter. The response of the various structural elements to their loading functions is determined so that failure in the flexural mode, rather than in one of the more brittle modes, is insured.

In the interest of brevity, the blast evaluation is limited to one example of each of the principal structural elements of the shelter. These elements are: the roof slab, the supporting beams, the bearing walls and the columns. For special cases, the Air Force Design Manual should be consulted.

A. Roof slab

The original design of the roof over the multipurpose room calls for 24-inch single Tees with a 10-inch concrete fill. This design was presumably intended to take advantage of the economy and other desirable characteristics ot prestressed construction. However, for blast loading, consideration should be given to cast-in-place construction so that full advantage may be taken of the 10-inch concrete fill which was obviously intended to provide barrier protection against radiation emitted by fallout on the roof. Thus for this sample evaluation the roof structures are assumed to be cast-in-place. This change does not significantly affect the general character of the structure.

The roof slab is assumed to behave as a one-way slab, spanning between the Tees and fixed at the ends.

1. Obtain Trial design.

a. Assume $p_m = p_{so} = 10$ psi

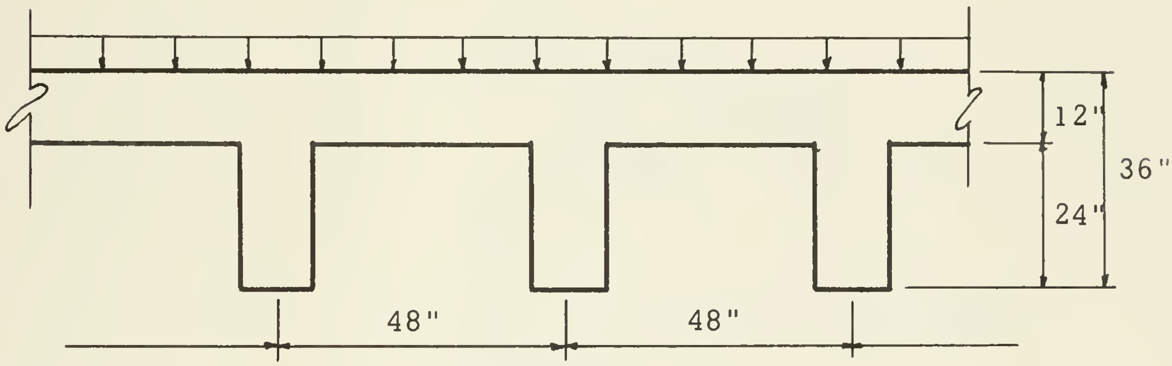
μ = 5 for flexure

μ = 1.3 for shear

μ = 1.3 for diagonal tension

b. Trial depth of slab

For shielding purposes, this design utilizes a 10-inch slab on 24-inch Tees. Try a 12-inch slab, assuming d = 9 inches.



Slab detail

c. Flexural steel requirements

As an estimate of the required flexural resistance of the member, the following equation, based on an idealized step-pulse loading function, can be used:

$$\frac{p_m}{q_y} = 1 - \frac{1}{2\mu} = 0.90 \qquad (28)$$

where

p_m = peak loading overpressure

q_f = flexural resistance of member

μ = ductility ratio

then $q_f = 11.1$ psi for $p_m = 10$ psi

and $q_f = 0.072\ (\phi_c + \phi_e)\ f_{dy}\ (\frac{d}{L})^2$ (3)

where

ϕ_c = percentage of tensile steel at midspan

ϕ_e = percentage of tensile steel at support

f_{dy} = dynamic steel yield strength

d = effective depth of tension steel reinforcement

L = length of span

$$(\phi_c + \phi_e) = \left(\frac{q_y}{0.072\ f_{dy}}\right)\left(\frac{L}{d}\right)^2$$

Let $\phi_c = \phi_e$

then $\phi_c = \phi_e = (11.1/0.144 \times 5 \times 10^4)\ (\frac{48}{9})^2$

$\phi_c = 0.0437\%$

Since the minimum steel requirement is 0.20% for shrinkage and temperature reinforcement, try d = 6 inches; i.e., place temperature steel at mid-depth.

Then $q_f = 0.072\ (0.4)\ 5 \times 10^4 \times (\frac{6}{48})^2$

$q_f = 22.4$ psi $>$ 11.1 psi O.K.

Use #5 bars at 12 inches on center at mid-depth of the slab.

d. Check shear strength

$V_{ult} = 0.22\ f'_c ad$ (29)

where

V_{ult} = shear acting at a distance d/2 or 0.1 L away from the support, whichever is smaller

f'_c = concrete strength

a = width of slab (assume 12 in.)

d = effective depth of tension steel

and $$V_{ult} = q_v(L - 0.2L)\,a \qquad (30)$$

where

q_v = shear resistance

L = length of span

then $$q_v = \frac{0.22 f'_c d}{0.8L} \qquad (31)$$

for f'_c = 4000 psi

$q_v = 0.22 \times 4 \times 10^3 \times 6/0.8 \times 48$

q_v = 136 psi > 11.1 psi O.K.

Therefore the slab will not fail in shear.

e. Check diagonal tension strength

$$q_y = 3.5\sqrt{f'_c}\,(d/L)\,(a/b) \qquad (32)$$

where

q_y = resistance to diagonal tension

b = width of loaded area

here $\frac{a}{b}$ = 1, and

$$q_y = 3.5\sqrt{4000}\,\left(\frac{6}{48}\right)$$

q_y = 27.8 11.1 psi O.K.

Therefore the slab will not fail in diagonal tension and no web reinforcement is required.

f. Obtain fundamental period of flexural vibration

$$T = \frac{L^2}{85{,}000\ d\sqrt{\phi_c}} \qquad (33)$$

where

T = fundamental period of vibration

$$T = \frac{48^2}{8.5 \times 10^4 \times 6 \times 0.14}$$

T = 0.0323 sec.

2. Obtain loading function

From Figure 3-8 in the Air Force Design Manual, a two-triangle representation of the side-on overpressure function may be obtained. In this two-triangle representation, it is slightly conservative to ignore the drag component on the roof.

For a one-megaton surface burst and a peak side-on overpressure of 10 psi:

c_1 = 0.24

c_2 = $1.0 - c_1 = 0.76$

t_1 = 0.3 sec.

t_2 = 1.5 sec.

where

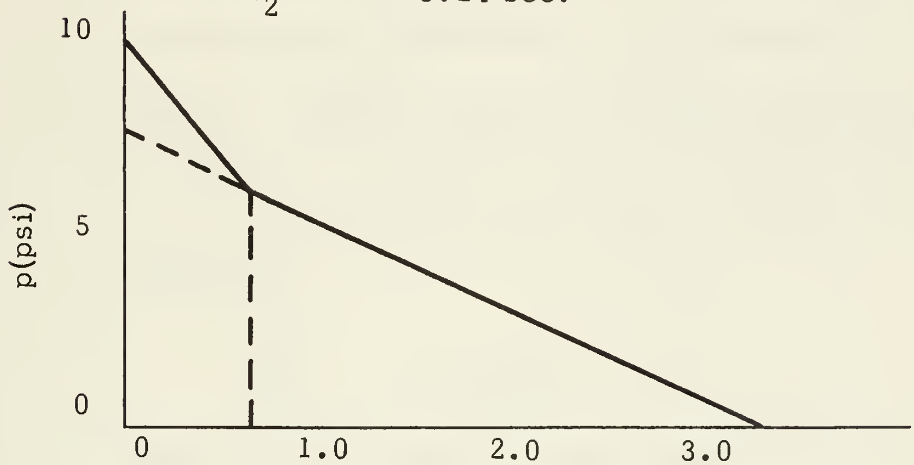
c_1, c_2 = pressure factors

t_1, t_2 = duration of effective overpressure triangles

For a ten-megaton surface burst the times above must be multiplied by $\sqrt[3]{10}$; then

$$t_1 = 0.65 \text{ sec.}$$

$$t_2 = 3.24 \text{ sec.}$$



Slab loading function

3. Determine flexural response of slab to above loading function.

a.

$$\frac{t_1}{T} = \frac{0.65}{0.0323} = 20.1$$

$$\frac{t_2}{T} = \frac{3.24}{0.0323} = 100.0$$

b. From Figure 9-1, <u>Air Force Design Manual</u> for u = 5.

$$F_1 = 0.92$$

$$F_2 = 0.91$$

where

F_1, F_2 = loading forces

c. The required yield resistance can be obtained from:

$$q_f = p_m \left[\frac{c_1}{F_1} + \frac{c_2}{F_2} \right] \tag{34}$$

or

$$q_f = 10 \left[\frac{0.24}{0.92} + \frac{0.76}{0.91}\right]$$

$$q_f = 10.95 \text{ psi} \cong 11.1 \text{ psi} \qquad \text{O.K.}$$

It could have been anticipated that the required yield resistance would approximate that estimated in the trial design. Whenever $\frac{t_1}{T} \geq 5$, the design yield resistance of the structure may be approximated closely by the expression

$$\frac{p_m}{q_y} = 1 - \frac{1}{2\mu} \tag{28}$$

which was developed for a step pulse.

The side-on overpressure and range for a ten-megaton surface burst which correspond to the calculated flexural resistance can be obtained at this point if desired.

B. T-beams

Assume T-beams are poured monolithically with the exterior wall so that they may be treated as essentially fixed at the ends. The flexural rigidity of the bearing wall is much greater than that of the fifty-foot span T-beam. As shown in Figure 17, the single Tees were originally 24 inches deep and placed at 4 feet on centers.

1. Obtain trial design.

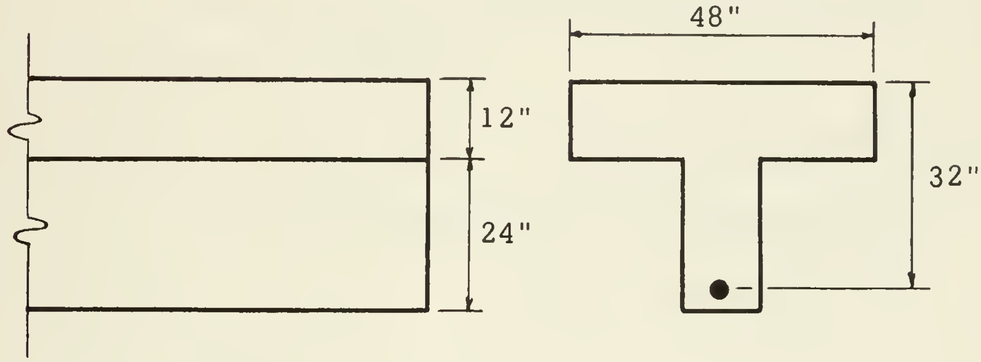
a. Assume $p_m = p_{so} = 10$ psi

$\mu = 5$ for flexure

$\mu = 1.3$ for shear and diagonal tension

b. Trial depth of beam

Using the slab depth obtained above, and the 24-inch depth of web shown on the architectural drawings, try d = 32 inches



T-Beam detail

c. Flexural steel requirements

As estimated in obtaining the trial slab design, for a peak side-on overpressure of 10 psi and u = 5, the flexural resistance required is about 11.1 psi. The dead load of the slab is about 1.1 psi, and that for the stem is about 0.3 psi. Then the total design load is 12.5 psi.

Assuming that the neutral axis is in the slab

$$q_f = 0.072 \, (\phi_c + \phi_e) \; f_{dy} \left(\frac{d}{L}\right)^2 \qquad (3)$$

Let $\phi_c = \phi_e$

then $\phi_c = \phi_e = (12.5/0.144 \times 5 \times 10^4) \left(\frac{600}{32}\right)^2$

$$\phi_c = 6.15 \times 10^{-1} = 0.615\%$$

$$A_s = \phi_c bd \tag{35}$$

where

A_s = Area of tension steel required

A_s = $0.00615 \times 48 \times 32 = 9.45 \text{ in.}^2$

Use 12 #8 bars in three layers of four bars each in the 12-inch wide stem.

At the support, the required steel in the flanges may be calculated from the following expression:

$$q_f = 0.072(\phi_c + \phi_e) f_{dy} \left(\frac{a}{b}\right) \left(\frac{d}{L}\right)^2 \tag{3}$$

where

a = width of stem

b = width of contributory load area

Let $\phi_c = \phi_e$

and $\phi_e = 12.5/0.144 \times 5 \times 10^4 \left(\frac{48}{12}\right) \left(\frac{600}{32}\right)^2$

$\phi_e = 2.46\%$

$$A_s = \phi_e bd \tag{35}$$

$A_s = 0.0246 \times 12 \times 32$

$A_s = 9.45 \text{ in.}^2$

Use 12 #8 bars in the flange at the support.

d. Check shear strength

$$V_{ult} = q_v(L - 0.2L)b \tag{30}$$

$$q_v = \frac{0.22 f'_c}{0.8} \times \frac{d}{L} \times \frac{a}{b}$$

$q_v = 14.6 \text{ psi} > 12.5 \text{ psi}$ O.K.

e. Check diagonal tension strength

$$q_y = 3.5\sqrt{f'_c}\left(\frac{d}{L}\right)\frac{a}{b} \qquad (32)$$

$$q_y = 2.95 \text{ psi} < 12.5 \text{ psi}$$

Therefore web reinforcement is required.

The yield resistance of the T-beam with diagonal tension reinforcement may be calculated from the following:

$$q_y = 100\left(1 + \frac{3}{2}\frac{\phi_e}{\phi_c}\right)\left(\frac{1}{2+\gamma}\right)\sqrt{\phi_c f'_c}\left(1+\frac{2\phi_v}{10^5} f_{dy}\right)\left(\frac{d}{L}\right)^2\left(\frac{a}{b}\right) \qquad (36)$$

where

q_y = diagonal tension resistance

ϕ_e = ϕ_c, calculated as for rectangular section of width a(ϕ_e = 2.46%)

γ = ratio of compression to tension steel at midspan (γ = 0)

ϕ_v = percentage of web steel

a, b, d, L, f'_c, and f_{dy} are as previously defined.

Try ϕ_v = 0.50% (minimum web reinforcement)

Then $q_y = 100(2.5)(0.5)\sqrt{9840}\,(1.5)\left(\frac{32}{600}\right)^2\left(\frac{12}{48}\right)$

$q_y = 13.2 \text{ psi} > 12.5 \text{ psi}$ O.K.

f. Obtain fundamental period of flexural vibration

$$T = \frac{L^2}{85{,}000 d\sqrt{\phi_c}} \qquad (33)$$

$$T = (600)^2/8.5 \times 10^4 \times 3.2 \times 10 \times \sqrt{0.615}$$

$$T = 0.168 \text{ sec.}$$

2. Obtain loading function.

The loading function is the same as that for the slab (p.   ).

3. Determine the flexural response of T-beam to loading function.

a.

$$\frac{t_1}{T} = \frac{0.65}{0.168} = 3.87$$

$$\frac{t_2}{T} = \frac{3.24}{0.168} = 19.3$$

b. From Figure 9-1, Air Force Design Manual for u = 5

$$F_1 = 1.04$$

$$F_2 = 0.92$$

c. The required yield resistance can be obtained from

$$q_f = p_m \left[\frac{c_1}{F_1} + \frac{c_2}{F_2} \right] \qquad (34)$$

$$q_f = 10 \left[\frac{0.24}{1.04} + \frac{0.76}{0.92} \right]$$

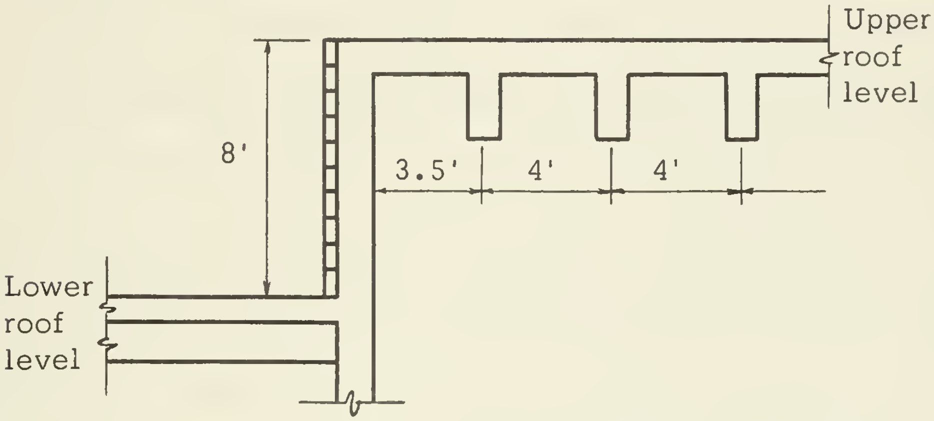
$$q_f = 10.6 \text{ psi} \cong 11.1 \text{ psi} \qquad \text{O.K.}$$

Thus the T-beams are satisfactory as designed.

C. Bearing wall

As shown on the architectural drawings, the bearing walls are of 16-inch-thick grouted brick. Although a brick wall of these dimensions is more resistant to blast than a conventional brick wall, it cannot be relied upon to provide support for the roof at the 10 psi overpressure level. A reinforced concrete wall is required. For blast loading, the wall can be considered to behave as a one-way slab except near the ends. The wall section supporting the roof over the

multipurpose area can be considered as a one-way slab 8 feet high by 12 inches thick, as shown below. The wall can be faced with 4-inch brick to provide required mass thickness and to maintain the architectural treatment of the original design. No brick facing should be provided on the interior in order to avoid potential missile hazards.



Bearing wall detail

1. Obtain trial design.

   a. Assume $p_m = 25$ psi $= p_r$ (reflected overpressure)

   $\mu = 5$ for flexure

   $\mu = 1.3$ for shear and diagonal tension

   b. Trial depth, $d = 9$ inches

   c. Flexural steel requirements

   Let $q_f = p_m = 25$ psi for trial

   $$q_f = 0.072(\phi_c + \phi_e)\, f_{dy} \left(\frac{d}{L}\right)^2 \qquad (3)$$

   Let $\phi_c = \phi_e$

   $$\phi_c = \phi_e = (25/0.144 \times 5 \times 10^4)\left(\frac{96}{9}\right)^2$$

$$\phi_c = 0.396\% \text{ say } 0.4\%$$

$$A_s = .004\, bd \qquad (35)$$

$$A_s = 0.432 \text{ in.}^2$$

Use #6 bars at 12 inches on center in both faces at midspan and at the supports. Although a thinner wall would suffice for this case, the depth is needed to develop moment resistance where the wall joins the roof. An effect which is not considered here is that of the axial load in the wall produced by loading on the roof. Because the shock wave takes a finite time to travel across the roof, it is quite possible that the moments and shears in the wall will develop to their maximum values before the roof is entirely loaded. Thus the effect of the axial load from the roof may be conservatively ignored.

d. Check shear strength

$$q_v = \frac{0.22 f'_c}{0.8} \frac{d}{L} \qquad (31)$$

$$q_v = (0.22 \times 4 \times 10^3 / 0.8)(\frac{9}{96})$$

$$q_v = 103 \text{ psi} > 25 \text{ psi} \qquad \text{O.K.}$$

e. Check diagonal tension strength

$$q_y = 3.5\, f'_c \; (\frac{d}{L}) \qquad (32)$$

$$q_y = 3.5 \times 63.5\, (\frac{9}{96})$$

$$q_y = 20.8 \text{ psi} < 25 \text{ psi}$$

May need web reinforcement. (See step 4)

f. Obtain fundamental period of flexural vibration

$$T = \frac{L^2}{85{,}000 d \sqrt{\phi_c}} \qquad (33)$$

$$T = 96^2 / 8.5 \times 10^4 \times 9 \sqrt{0.4}$$

$$T = 0.019 \text{ sec.}$$

2. Obtain loading function.

The peak reflected overpressure at 10 psi incident may be calculated from the following expression:

$$p_r = 2p_{so} \left[\frac{7p_o + 4p_{so}}{7p_o + p_{so}} \right] \qquad (37)$$

where

p_r = peak reflected overpressure

p_{so} = peak side-on overpressure

p_o = ambient atmospheric pressure

$$p_r = 2(10) \left[\frac{7 \times 14.7 + 4 \times 10}{7 \times 14.7 + 10} \right]$$

$$p_r = 25.3 \text{ say } 25 \text{ psi}$$

The duration of the spike of reflected overpressure cannot be calculated exactly but may be conservatively assumed to be equal to the clearing time for the projected portion of the structure.

$$t_c = \frac{3H}{U} \qquad (38)$$

where

t_c = clearing time

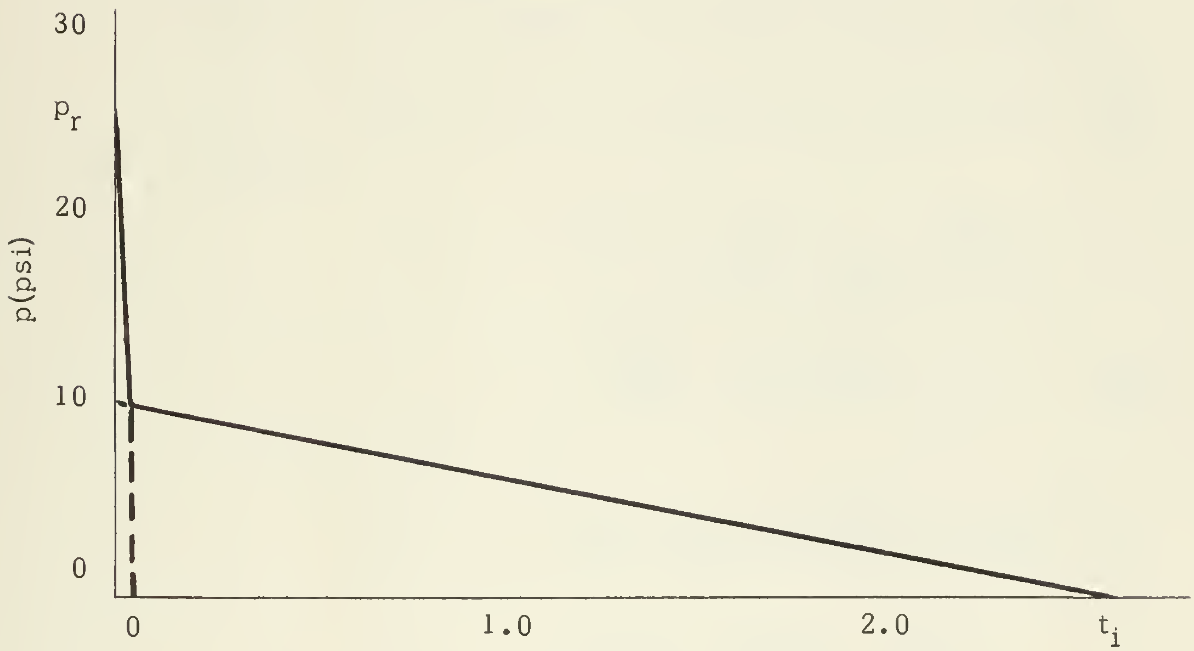
H = height of wall above roof level

U = velocity of shock front

For H = 10 ft. and assuming $U = 1400$ fps

t_c = 0.0214 sec.

Using a total equivalent impulse duration of $t_i = 2.6$ sec. (obtained from Figure 3-7, Air Force Design Manual) an idealized loading function may be obtained as shown below.



Bearing wall loading function

3. Determine flexural response of wall to loading function.

a. $$\frac{t_c}{T} = \frac{0.0214}{0.019} = 1.13$$

$$\frac{t_i}{T} = \frac{2.6}{0.019} = 136.8$$

b. From Figure 9-1, Air Force Design Manual,

F_1 = 1.4

F_2 = 0.91

c. The required yield resistance can be obtained from

$$q_f = p_m \left[\frac{c_1}{F_1} + \frac{c_2}{F_2}\right] \tag{34}$$

$$q_f = 25 \left[\frac{0.6}{1.4} \quad \frac{0.4}{0.91}\right]$$

$$q_f = 22 \text{ psi} \cong 25 \text{ psi} \qquad \text{O.K.}$$

4. Check web steel requirements.

Referring to the preceding calculations only the diagonal tension strength of the wall appears less than 22 psi. Check equation

$$q_y = 100\left(1+\frac{3}{2}\ \frac{\phi_e}{\phi_c}\right)\left(\frac{1}{2+\gamma}\right)\sqrt{\phi_c f'_c}\ \left(1+\frac{2\phi_v}{10^5}\ f_{dy}\right)\left(\frac{d}{L}\right)^2\left(\frac{a}{b}\right) \tag{36}$$

Let γ and $\phi_v = 0$

$$q_y = 100(2.5)(0.5)\sqrt{1600}\ (1)\left(\frac{9}{96}\right)^2 (1)$$

$$q_y = 44 \text{ psi} > 22 \text{ psi} \qquad \text{O.K.}$$

No web reinforcement is required, and the bearing wall is satisfactory as designed.

D. Interior column

The columns at the north and south ends of the multipurpose area support, through beam action, the 16-inch bearing wall designed above and part of the roof load from the surrounding classroom areas. As scaled from the drawings, the columns are 10 feet in height and 20 inches by 20 inches in cross section. Assume column is axially loaded.

1. Obtain trial design.

For the trial design, use the indicated cross-section of 20 inches by 20 inches and assume a total percentage of reinforcing steel of 2 per cent.

a. Check unsupported length

$$L/t < 15 \text{ for short column}$$

where

L = unsupported length of column

t = least width of column

$$120/20 = 6 < 15 \qquad \text{O.K.}$$

b. Determine ultimate load

$$P_u = (0.85\, f'_{dc} + (\phi_t/100)\, f_{dy})\, A_c \qquad (39)$$

where

P_u = axial load capacity of a dynamically loaded column

f'_{dc} = dynamic concrete strength

f_{dy} = dynamic steel yield strength

ϕ_t = total percentage of reinforcement

A_c = area of concrete

then $P_u = (0.85 \times 5000 + (2/100) \times 50\,000)\ 400$

$P_u = 2{,}100{,}000\ \#$

2. Obtain actual load.

a. Contributory dynamic load areas

Roof over multipurpose area

4' x 18' x 10 psi x 144 = 104,000#

Roof over classrooms

6' x 18' x 10 psi x 144 = 156,000#

b. Dead and live load of structural elements

Slab and beams over multipurpose area

4' x 18' x 245 psf = 18,000#

Slab and beams over classrooms

6' x 18' x 170 psf = 18,000#

Bearing wall

8' x 18' x 1.33' x 150 pcf = 29,000#

Total load = 226,000#

Because of the particularly serious consequences of a column failure when the column supports a roof subjected to blast loading, the Air Force Design Manual recommends that the resistance of the column be either twice the peak blast pressure times the tributary roof area, or the maximum resistance of the supported elements, whichever is smaller. In this case, assume a total load of

226,000# x 2 = 452,000# $<$ 2,100,000# O.K.

Thus the columns are satisfactory as designed.

Thermal Evaluation

No major difficulties were encountered in upgrading the example building to meet the additional requirements of increased resistance to

the fire effects of nuclear weapons. As the building is shown on the drawings as being isolated from any serious exposure fire hazard, an adjacent office building of five stories was assumed to be situated 100 feet from the school for example purposes. The thermal evaluation was conducted using as a basis seven key elements concerned with thermal protection, as outlined below.

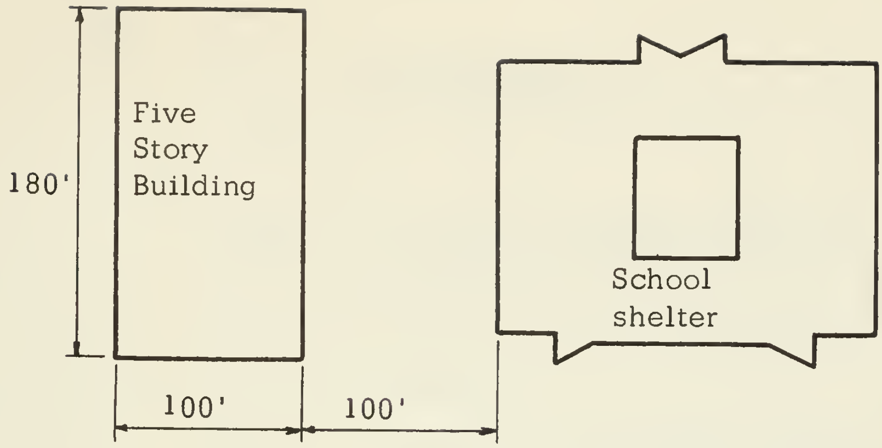
1. Site layout

The location of the structure allows good access for fire fighting by outside sources. The building itself affords access to firemen and equipment by means of the numerous windows and doors. Another advantage is that the structure is situated on ground which slopes gently away from the building.

Some dense vegetation is noted near the building. It is recommended that such planting be avoided close to the structure, first, because of the additional fire hazard, and second, because of the possibility that it could obstruct fire-fighting equipment.

The parking lot, when filled to its capacity of 45 cars, each having an assumed fire load of 500# (tires, gasoline, oil, grease, paint, upholstery, etc.) is situated 50 feet from the building and exposes a fire resistive wall and one of the classrooms. An estimate of the exterior fire exposure of the parking lot to the school is less than two minutes.

It is assumed that a five-story office building is located 100 feet from the school, as shown below.



Exposure building situation (plan view)

Exposure building data:

Multistory office building, roof noncombustible.

Estimated fire load: 10 psf of floor area

Wood equivalent: 1.0

Window openings: 30%

$h_a = 5'$ $H_b = 56'$

$W_b = 90'$ $d_o = 100'$

In order to determine the exposure severity index of the office building it is necessary to solve the equation

$$E_{eb} = F_w(0.10\ q_{eb}) \tag{4}$$

where

E_{eb} = exposure severity index for exposure building

F_w = shape factor for wall of exposure building

Solving for q_{eb}:

$$q_{eb} = (RWF)(HF)(w_{eb}) \quad (7)$$

where

RWF = Roof and wall factor (Table 9)

HF = Heat factor (average wood equivalent (Table 4)

w_{eb} = weight of combustible material, psf of building surface

then $q_{eb} = (0.7)(1.0)(100x180x5x10/100x180+56x560)$

$q_{eb} = 12.7$ psf

Solving for F_w:

$$F_w = F_1 + F_2 \quad (20)$$

where

$$F_1 = f(X_1, Y_1) \text{ (Table 8)} \quad (21)$$

$$F_2 = f(X_1 Y_2) \text{ (Table 8)} \quad (22)$$

$$X_1 = w_b/d_o \quad (23)$$

$$Y_1 = h_a/d_o \quad (24)$$

$$Y_2 = (H_b - h_a)/d_o \quad (25)$$

then $X_1 = 90/100 = 0.9$

$Y_1 = 5/100 = 0.05$

$Y_2 = (56 - 5)/100 = 0.51$

$F_1 = f(0.9, 0.05) = 0.019$

$F_2 = f(0.9, 0.51) = 0.168$

and $F_w = .019 + .168 = 0.187$

finally, $E_e = 0.187(0.10 \times 12.7)$

$$E_e = .238 \text{ hour, say } 1/4 \text{ hour}$$

Thus the exposure severity of the multistory office building to the shelter is negligibly small so long as thin, combustible materials are shielded. It can be seen in Table 2 that practically any load-bearing masonry wall offers sufficient protection against a fire severity of 1/4 hour.

2. Structural considerations

It is indicated from rays sketched on both the elevation and plan views of the building that thermal impingement is likely to occur on the floor and all walls of the classrooms of the building. It is recommended that attention be given to methods of shielding the interior of the classrooms from these rays. This may be accomplished through use of additional structural baffles or suitable drapes, as well as by raising the sill height of the windows.

All conditions for life safety appear to have been met in the original design of the corridors and exits of this structure. Shelter storage is noted on the corridors, but it is assumed that compartmented, locked, metal storage cabinets are utilized and that no unusual hazard is presented here.

It is noted that hazardous areas of more than normal fire loading are located adjacent to corridors in some cases. These areas must be provided with fire resistant doors and partitions so that the escape routes will not be subjected to this fire hazard.

3. Compartmentation and firestops

This structure offers a high degree of compartmentation for the containment of fire. In general, all compartments are protected with a fire wall or a fire partition by virtue of the reinforced concrete construction employed in the building. The use of reinforced concrete bearing walls should offer a minimum of four hours fire resistance which far exceeds the resistance required consistent with the fire load presumed for the building.

Some improvements are needed in the kitchen, which is classified as a hazardous area. It is recommended that the kitchen be provided with additional fire resistant barriers to isolate it from the remainder of the building. An alternate solution would be to place the kitchen on an outside wall and better use the built-in fire protection afforded by the fire resistive exterior walls.

4. Grouping of hazardous areas

In this design, the mechanical and electrical equipment rooms have been separated from the main structure, which is desirable from the thermal point of view, provided the separate installation has adequate protection to prevent blast damage and the possibility of secondary fires. Attention should be given to the janitors' storage areas as well as the kitchen area, as mentioned above, to insure that adequate protection is provided to prevent fire spread should it occur in these hazardous areas.

5. Furnishings and materials of construction

Where thermal radiation can enter the building, primary fires may

occur, depending upon the materials which the thermal rays encounter. No thin cellulosic materials should be used on surfaces, including furniture, where the rays could impinge. If the use of acoustical tile is planned, it should be of mineral fiber, and no combustible materials should be used in its installation.

Fire resistant doors and partitions should be provided consistent with the interior fire load index of each compartment, which can be determined by the method outlined on pages 64 to 66 . The minimum fire severity index anticipated in this building is 3/4 hour, which is slightly higher than that indicated by a fire load index of 5 psf. Special consideration in this matter should be given to hazardous areas such as mechanical and electrical equipment rooms.

6. Firefighting from within

The layout of the building with its near symmetrical arrangement of classrooms provides for convenient fighting of fire from within the shelter by self-help processes. Extinguishers are shown on the plans. Improvement of fire fighting from within would consist principally of an increase in the amount and distribution of the fire-fighting equipment, both active and passive.

Sprinkler protection should be provided in areas with more than normal fire load, such as the kitchen area. The sprinkler system should be provided with an independent water supply. In addition to the sprinkler system, it is recommended that a hose system be installed midway between the ends of the corridor serving the class-

rooms on the east and west sides of the building.

Other self-help devices which should be provided include: a pressurized water extinguisher at each corner of the multipurpose room, two dry chemical extinguishers in the kitchen area, and a dry chemical or carbon dioxide extinguisher in the mechanical room.

7. Smoke and heat venting

Smoke and heat venting of the classrooms is assumed to be adequate by virtue of the doors and windows to the outside. However, the plans do not indicate smoke-venting facilities for the main shelter area. Should fire occur in the shelter or surrounding rooms it is necessary that the products of combustion be disposed of immediately. Mechanical smoke-venting installations can be installed if necessary. All standard air handling equipment should be provided with heat and smoke sensing devices and gasketed dampers to prevent circulation of the products of combustion. Outside vent openings should be designed to resist blast effects. Adequate noncombustible seals should be provided around piping in risers and other openings to prevent the spread of smoke and fire gasses.

Radiation Evaluation

All changes recommended to increase the blast and thermal resistance of this structure either maintained or increased the mass thickness and amount of baffling originally provided for protection from fallout radiation. As the sheltered portions of the structure were

originally designed for a high level of radiation protection, having a protection factor of 100 or better, the protection factor is less sensitive to change than it would be at lower protection levels. The recommended structural changes for the subject building result in corresponding changes in the protection factor which while favorable, are of a magnitude somewhat less than 5%.

Architectural Considerations

All changes recommended to increase the resistance of the structure to the integrated effects of nuclear weapons may be incorporated without altering the original functional and aesthetic characteristics of the school. It should be possible to increase the fire resistance of interior partitions and doors with no obvious changes in design. Brick facing should be used on the exterior reinforced concrete walls in order to maintain the original appearance of the building.

RESULTS AND CONCLUSIONS

Blast Investigation

A. General description of the shelter concepts employed

The basic shelter concepts utilized in the school designs can be categorized with more than one concept being used in some cases. Three basic approaches were employed in the design of above-ground shelters. These concepts are illustrated in Figure 19 and described below:

1. Core Shelter

   This concept utilizes a core shelter area surrounded by classrooms open to the outside. Solutions of this type either provide the necessary wall mass thickness in the interior partition around the shelter core or utilize the mass thickness of the exterior wall in conjunction with that of the interior partition.

2. Entire Building Shelter

   In this case the entire structure is used as a shelter with the required mass thickness being provided completely by the exterior walls.

3. Upper Story Shelter

This design incorporates shelter in the upper stories of a multi-story structure with the required mass thickness being provided by means of pivotable radiation/sun shields.

For below-ground shelters two basic approaches were employed, as shown in Figure 19.

1. Underground Shelter

The entire structure is placed underground in this approach. In some cases natural light was admitted by wells around which the classrooms and offices were clustered.

2. Basement Shelter

Two-story structures can be employed with one level below ground (a basement). Another method utilizes a depressed lower story which is surrounded by a moat in order to limit the plane of fallout contamination. A third variation of this concept employs two single-story structures on a side-hill, each having one wall (downhill) exposed and the other below ground.

The structural systems employed were more uniform than the radiation shielding solutions. Without exception, the roofs over all shelter areas were of reinforced concrete construction, and were supported by either beams and columns or load bearing walls. Wall construction consisted of reinforced concrete, with and without

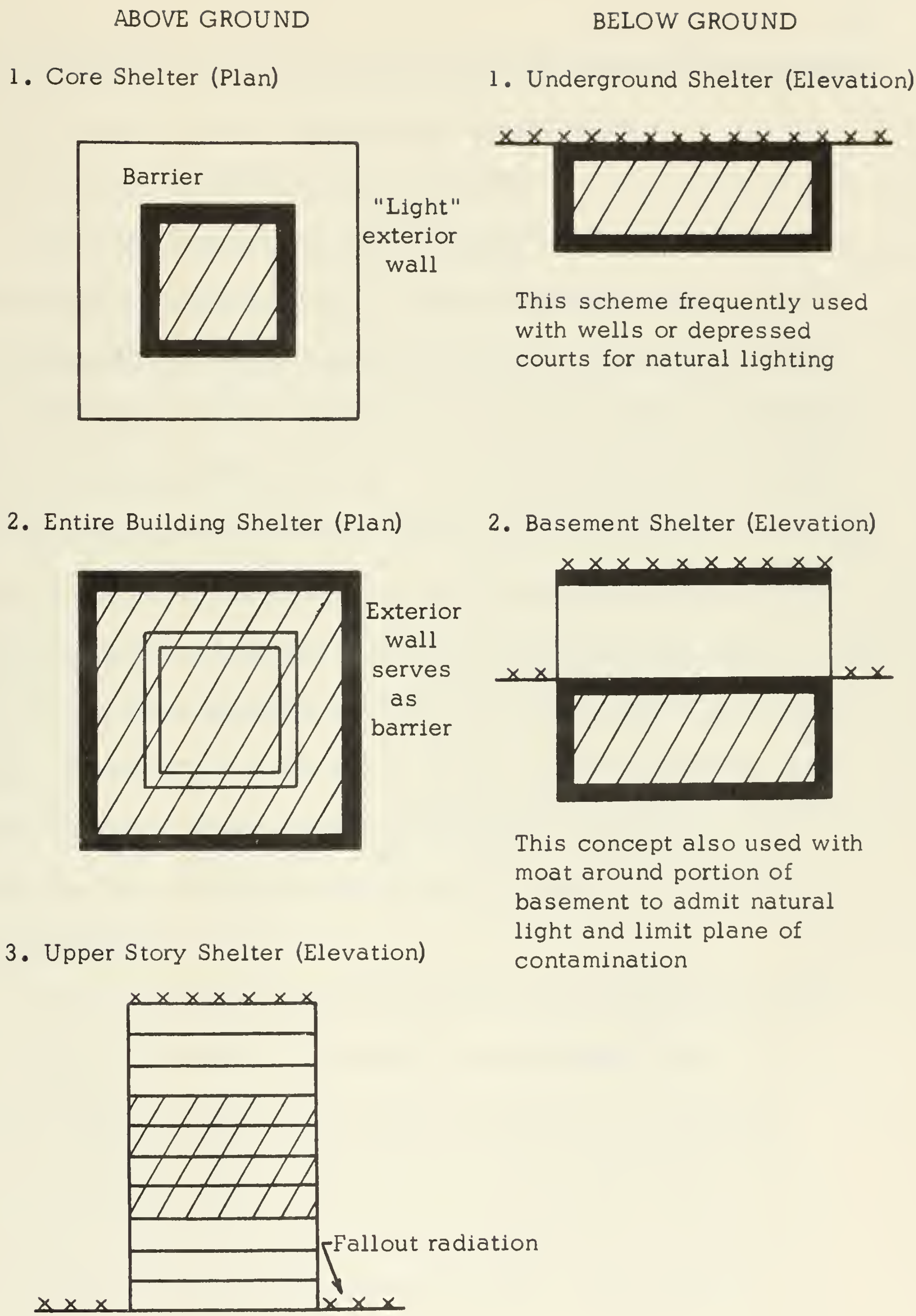


Figure 19. Basic Shelter Concepts Employed

brick or stone facing: or concrete block with and without facing materials. In one design walls were indicated as stone and mortar.

B. Relative merits of the basic solutions

Of the above-ground concepts, the best solution is that which incorporates the entire building as a shelter (Number 2 in Figure 19). In this approach, the entire structure should be of reinforced concrete, and designed such that it can withstand an incident side-on overpressure of 10 psi. Subsequent to the arrival of a blast wave of this intensity the entire structure would remain standing. The only damage anticipated would be glass breakage in the doors, and these should be baffled to prevent flying glass fragments from injuring the shelter occupants. This concept also offers excellent protection from thermal radiation. The primary disadvantages of this type of structure are that the classrooms would not receive natural lighting (although this criterion may have some advocates) and that it may reflect more expense than the core shelter concept.

The core shelter is less expensive but also provides less total shelter area. In addition, where there are large glass areas in the exterior walls, the classrooms would be subjected to considerable thermal radiation, which could result in a serious fire hazard. After the arrival of the shock wave it may be assumed that the classrooms surrounding the core will have been destroyed. This assumption is based on the lighter roof, wall, and partition construction prevalent in this area. However, the core would remain intact and, assuming

properly baffled entryways, would protect the occupants from flying glass fragments and other missiles and, subsequently, from fallout radiation.

The upper-story shelter is the least desirable approach for several reasons. First, there is the problem of access and egress under emergency conditions. Second, although it is possible to design such a structure to withstand reasonably high overpressures, in all but the most unusual circumstances, the structure would be more expensive than a one-story building of the same floor area.

Below-ground shelters are inherently more resistant to blast effects than above-ground shelters. However, since a practical upper limit for an "open" shelter of about 10 psi exists, this advantage is partially lost, as protection in this range can be incorporated into above-ground shelters at reasonable expense.[19] The principal advantage gained by placing a portion of a structure underground is increased protection against fallout radiation. For the same wall and roof mass thickness the fallout protection afforded by a below-ground structure is much greater than that for an above-ground structure.

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[19] In a recently published work by C.S. White, Tentative Biological Criteria for Assessing Potential Hazards from Nuclear Explosions DASA 1462 (Albuquerque, N.M.: Lovelace Foundation for Medical Education and Research, Dec., 1963), an overpressure of about 12 psi (assuming a sharply rising pressure and a duration in excess of 400 milliseconds) is indicated as the threshold of serious lung damage to large mammals.

Thermal Investigation

While resistance to the three basic types of fire hazard accompanying a nuclear explosion has been used as the basis of analysis of the school designs, and should be the basis for the analysis or design of any structure intended to resist the thermal effects of nuclear weapons, certain key elements which could serve as guideposts for all fire-resistant construction have become apparent. These key elements are listed below, accompanied by a brief discussion of the function of each in creating a fire resistive structure.

1. Site layout
2. Structural considerations
3. Compartmentation and firestops
4. Grouping of hazardous areas
5. Furnishings and materials of construction
6. Firefighting from within
7. Smoke and heat venting

1. Site layout

Spread of fire from a burning building to an adjacent shelter by sustained radiation from the fire coupled with heat transfer by convection is a considerable hazard. Exposure fires could be the most important fire problem in the event of a nuclear attack. The location of a structure is of fundamental importance from the standpoint of the hazard of exposure fires. In this respect, the building density or "builtupness" of an area, the type of structures which

exist, and the width and nature of firebreaks must be considered. The building should be placed in the most advantageous position to minimize exposure from the surrounding properties. If it is not possible to place the structure on an ideal site, protection from exposure fires must be incorporated into the design considerations.

Dense vegetation should not be close to buildings, particularly in the case of tall trees. In addition to creating a possible fire hazard it could offer obstructions to fire-fighting equipment.

Stone or masonry fences, retaining walls, steep banks, or pits could hamper fire-fighting efforts from outside sources, and may, in the case of masonry fences, present a missile problem. Free standing walls which are a part of the shielding should be kept a minimum of 12 feet from the structure depending on the access requirements of local fire-fighting services.

2. Structural considerations

Thermal rays sketched on section views of the plans impinge on the interior surfaces of structures shown in some designs. Depending on the height of burst the ray strikes the wall or the floor, the walls being more vulnerable to a surface burst. These thermal rays could result in the ignition of thin combustible materials in the interior of the structure. To minimize the effect of thermal rays impinging on the interior of the structure, the following methods could be employed:

a. Roof Overhang

b. Baffles

c. Increased sill height of windows

d. Drapes of noncombustible reflective material

e. Screening

f. Fire resistant material for all exposed areas

Where the threat of exposure fires exists, construction should be such that the requirements to resist ignition by exposure fires as outlined on pages 55 to 66 are satisfied.

Corridors and exists should satisfy building exit codes and should be identified and kept clear at all times. Where shelter storage is along corridors, it should be in compartmented, locked metal storage cabinets. In underground structures for which no codes have been developed, it is recommended that corridor and exit widths be increased to compensate for the lack of windows which could be used in fighting fires and for escape.

Poor housekeeping and storage conditions can create a considerable fire hazard, but the avoidance of structural features inviting unusual storage can do much to eliminate this problem.

3. Compartmentation and firestops

Following the ignition of combustibles, limitations must be placed upon the development and spread of fires to provide for the safety of the building and its occupants. When the building is divided into fire areas by use of suitable barriers, a fire is limited to the

compartment in which it originates. Separation of the building into compartments is accomplished through use of fire walls or fire partitions. Open plan or semi-open plan type of structures should be divided into compartments to establish fire areas. The open type of structure complicates fire protection, whatever the origin of the fire. Under ordinary circumstances escape is possible to the outside of the building, but under conditions of nuclear attack, reliance must be placed on fire control by compartmentation.

It is of little use to specify compartmentation in a shelter only to have the interior doors or walls removed by nuclear blast effects. Were this to occur, flame and smoke might enter the shelter area and the fire area or compartmentation concept would be lost, making control of the fire difficult. It is desirable that some degree of blast resistance be included in the compartmentation elements of a structure to reduce this hazard. At the same time this would reduce the danger of fire ignition due to secondary blast effects.

4. Grouping of hazardous areas

Hazardous areas are areas of more than normal fire load or those where ignition of fires is most likely to take place, such as mechanical and electrical equipment rooms, janitor storage rooms, and kitchens. If such areas can be grouped, the probable number of ignition points in a structure is lessened, and the fire compartmentation concept has a better chance of operating as planned. Also, it

would be more convenient and less expensive to provide some form of blast and fire resistant protection for these areas if they are grouped. Finally, grouping of hazardous areas would assist in the economical employment of a partial interior sprinkling system.

5. Furnishings and materials of construction

The selection of materials of construction for a shelter should be based to some degree on room usage and the corresponding fire load. The fire resistive properties of shelter materials should be considered with the same attention that is paid to their strength properties. A fire load should be developed for each compartment of the structure so that the expected fire severity can be determined and the required fire resistant materials used.

Selection of materials and furnishings for the interior of a building can have a marked effect on the rate and degree of fire spread. Ceiling and floor surfaces should be of noncombustible material, or of material installed in such a manner that it would not contribute to fire spread; and should leave no concealed spaces.

No thin cellulosic materials should be used on any surface, including furniture, which could be exposed to thermal radiation.

6. Firefighting from within

Sprinkler protection should be provided in areas with greater than average fire loads. If these hazardous areas are grouped, a more economical installation can be effected. Sprinkler protection

has been proven effective in peacetime and should operate equally well in a warfire environment. A dependable, private water supply is preferable to public distribution systems due to the danger of blast damage. Other active measures such as hose systems and individually operated fire extinguishing equipment should be available to extinguish incipient fires which could occur through thermal ignition or other causes. The capacity to eliminate small fires in the early stages is of considerable importance in maintaining the integrity of the shelter.

7. Smoke and heat venting

In addition to protection from flame and radiant heat, attention should be given to methods of protecting a shelter from the effects of smoke, dust, and fire gasses. Heat and smoke venting should be given specific attention in shelter design. Venting can be incorporated through use of windows or doors where they extend to the ceiling. There is no formula for smoke venting from ordinary fires, but an area of five percent of the compartment area should be sufficient. Venting of compartments around the shelter area should also be incorporated. Smoke venting may also be accomplished through use of mechanical smoke-venting installations.

Adequate noncombustible seals should be provided around piping in risers and other openings to prevent the spread of smoke and fire gasses. All installations normally used for handling air should be equipped with heat and smoke sensing devices and gasketed dampers to prevent circulation of the products of combustion.

Radiation Investigation

The requirements for mass thickness and shielding to increase a structure's resistance to the blast and thermal effects of nuclear weapons are generally of the same nature as the requirements for protection against fallout radiation. Because of this, the changes recommended to improve the resistance of the school designs to the integrated effects of nuclear weapons (e.g., substitution of reinforced concrete for concrete block walls, increased baffling of entranceways) did not have adverse effects on the radiation resistance of the schools, and in many cases, protection factors were increased.

Conclusions

The analysis of the school fallout shelter designs clearly indicates that significant increases in resistance to blast overpressures and thermal hazards can be achieved with few and minor changes in the basic architectural solution. Only a few structures would require significant architectural modification. This increased resistance can be achieved primarily by the use of reinforced concrete construction for walls and interior partitions in the shelter area, with fire-resistant design principles being incorporated as required.

In some cases, clerestories and other glass areas in the walls surrounding the shelter must be eliminated, and more attention given to the use of baffling to prevent inside damage to the shelter occupants from flying glass fragments and other debris.

Below-ground shelters of both the basement and buried type are inherently more resistant to blast and thermal hazards, and provide more effective protection against fallout radiation than above-ground shelters. However, the mass thickness required in the roof and walls of an above-ground structure to meet fallout shielding criteria are such that an overall blast resistance corresponding to 10 psi incident overpressure and significant thermal protection can be achieved with only minor modifications in designs incorporating fallout protection.

The increase from a blast resistance level of about 2 psi to about 10 psi incident, with a corresponding increase in thermal protection is not an insignificant one when consideration is given

to the very large area between the 2 psi and the 10 psi overpressure contours of a large yield weapon.[20] A simpler way of stating this is that the probability of survival for a structure having 10 psi shock resistance and fire resistant construction is significantly greater than that for a structure having 2 psi resistance without thermal protection.

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[20] The area between the 2 psi and 10 psi overpressure contours is in excess of 200 square miles.

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BIOGRAPHY

Dennis F. McCahill was born on December 12, 1939, in Monessen, Pennsylvania. He received his elementary and secondary education in Laurel, Maryland, and was graduated from St. Mildred's High School in 1957.

He attended the University of Maryland for one year, and then won an appointment to the United States Naval Academy, Annapolis, Maryland, which he entered in 1958. He was graduated with distinction in June of 1962 and accepted a commission in the Civil Engineering Corps, United States Navy.

His first assignment was a one year tour of duty at the Naval Auxiliary Air Station, Meridian, Mississippi, where he served as Maintenance Officer and Assistant Officer in Charge of Construction.

In June of 1963 he reported to Tulane University to undertake studies leading to the degree of Master of Science in Civil Engineering. While at Tulane he was elected to Tau Beta Pi, honorary scholarship fraternity, and Omicron Delta Kappa, honorary leadership fraternity. He was a member of the student chapter of the ASCE and served as president of the chapter in 1964. In May of 1965 he completed the coursework required for the degree of Master of Science.